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HEARING

Its Psychology and Physiology

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PERSPECTIVE

IN 1863 Helmholtz wrote his *Lehre von den Tonempfindungen*, bringing together the scattered facts about hearing and defining a field of scientific interest. There were then hardly more than a dozen important facts in this field and some were not very old. It is true that the mathematics of music, the facts of intervals and their ratios, had concerned mathematicians ever since Pythagoras, but the velocity of sound had not been measured until 1636, and it was not until 1660 that Boyle proved conclusively that a bell ringing in *vacuo* is inaudible. Galileo in 1638 worked out the chief laws of physical resonance and established firmly the principle that pitch is a function of frequency—a principle that stood until 1930. The tuning fork dates from 1714, and that year is also the date of Tartini's first mention of the difference tones, which were for a century called by his name. In 1830 Savart set the upper and lower thresholds of hearing at 24,000 and 8 vibrations per second, holding a card against the teeth of a rotating wheel in order to determine these limits. In 1843 Ohm formulated his acoustic law that the ear hears the harmonic components of a complex wave form, an analytic principle that gained universal meaning in the light of Fourier's theorem of 1822 for the analysis of any periodic wave into sinusoidal components. That, however, was altogether very little. There was not much known about hearing when Helmholtz wrote the *Tonempfindungen*.

Helmholtz himself, besides bringing the physical and physiological facts together, demonstrated the variety of combination tones and determined the perceptual character of beats. He established the primary nature of the vowels, and he proposed a theory of them with an experimental demonstration for the theory. His keen observation and his fertile imagination gave him a position on many topics, and again and again he has turned out to be right. It is the resonance theory of hearing,

however, that is his classic contribution in the field of auditory sensation

In spite of all the discussion that went on, really not so very much happened in the sixty years after Helmholtz. The problem of the nature of vowels has recurred constantly from Donders' experiments in 1870 and Hermann's theory of formants in 1895 until the present day. The auditory thresholds were determined by Preyer in 1876 and then by Luft in 1888. Stumpf, on the basis of very slight evidence, published his laws of tonal fusion in 1890, and they persisted in uncritical acceptance for at least thirty years. The chief facts of auditory localization were established in 1901 (intensity), 1908 (phase), and 1920 (time). There was a flurry in tonal attributes about 1913-1919. And all this while scientists made up theories of hearing. The frequency theory or telephone theory was first posed against Helmholtz's resonance theory. Helmholtz's theory was a place theory, in that it derived its cogency from Johannes Müller's doctrine of the specific energies of nerves: for a different pitch there must be always a different nerve fiber. Presently there came to be resonance theories that correlated pitch with the fiber excited and others that correlated pitch with the frequency of excitation, and there were also both place theories and frequency theories that rejected the notion of analysis by resonance. The establishment in 1912 of the all-or-none law of nervous conduction should have made trouble for all the theorists who naïvely assumed that loudness depends upon the intensity of the neural impulse, but it was really a dozen years before this difficulty was generally appreciated. In other words, there was in this field more effort than success. What was needed was the discovery of a new approach to the old problem.

That approach was made possible by the development of the electronic vacuum tube for the amplification of small potentials. Although the history of electrical amplification goes back to de Forest in 1907, it was the later commercialization of the radio that placed these techniques in the hands of physiol-

ogists and psychologists In 1929 Wever and Bray applied the new technique to the amplification of physiological potentials of the auditory mechanism and found that these potentials resemble the acoustic stimulus Later research showed that it is only the 'cochlear response' that nearly duplicates the stimulus, and that the action potentials of the nerve are limited, as might have been expected, by the all-or none law and the normal refractory periods It was, nevertheless, the discovery of this 'Wever Bray effect' that began the wave of investigation into the physiology of hearing that has been spreading since 1930 Aided by the physicists, the psychophysics of threshold values and of sensory equivalents has kept pace with this new experimental physiology Thus the reader of this book can see how much of the psychology and physiology of hearing has been learned within the last decade and also how little of it was the product of the preceding half century In this way he will be able to gauge for himself the potency of a discovery of a new technique Certainly we are ready now for a new *Lehre von den Tonempfindungen* to orient us among the complexities of the new physiological acoustics which is now so successfully answering questions which Helmholtz posed

EDWIN G BORING

PREFACE

HERE IS OUR BOOK. It was originally conceived in the high hope of doing justice to a subject of inquiry which, within a decade, has undergone impressive transformation. Now, with the finished manuscript before us on the table, we are aware that the field of audition is already on the point of expanding beyond the confines of a single volume. And we find that our original purpose has had to accede to the practical demands of space. The relations of the science of audition to architecture and applied acoustics, to speech and phonetics, to the problem of noise, and to music are some of our deliberate omissions.

We undertook the preparation of this volume for two reasons. We wanted to provide the students of psychology, physiology, acoustics, and otology with an inventory of the recent discoveries in the psychophysiology of hearing—discoveries which up to now have enjoyed relative seclusion in scientific periodicals, and we wanted to test the progress of the study of audition by casting up the balance in systematic form, taking stock of the gaps and deficiencies, and finding to what extent auditory research is able to yield a consistent point of view.

The value of this book as an aid to the student of hearing might have been improved by a different order of the chapters, although the present order was dictated by a desire to achieve a logical development of the subject matter, and not merely by the fact that a psychologist was responsible for most of the first half and a physiologist for most of the second half of the work. (Incidentally, both psychologist and physiologist did much re-writing of both halves.) The logic of the presentation is first to provide the student with the fundamentals of the science of sound—with a minimum of mathematics—and then to tell him what he hears when a sound reaches his ears, and what are the systematic relations between stimulus and sensation. Then, knowing what he hears, he is in a position to be told, beginning

with Chapter 10, how he hears it. The functional anatomy and physiology of the ear, therefore, is the subject matter of the later chapters. The reader who favors a different order can just as well read the last nine chapters immediately after Chapter 1. Numerous cross-references have been included to aid him.

A glossary of essential terms has been developed in the hope that it will prove useful as a convenient source of precise definitions, and two appendices have been added to provide convenient reference to some mathematical developments which may be beyond the interests of the general reader. A third appendix contains what we have found to be a very useful table for converting ratios of sound pressure or voltage into decibels.

We have tried throughout to present a systematic and consistent picture of the auditory process, but we find we have had surprisingly little to say about *theories of hearing*. This omission is probably not so much symptomatic of a personal lack of interest in 'theories' as it is indicative of a state of development in the science. Theories flourish on a certain sparseness of facts and wither in the face of abundance. When all the relations are known, alternative theories are no longer possible, and, if a present inventory of the facts of audition leaves little room for theories of hearing—in the nineteenth-century meaning of the phrase—that situation must be accounted a sign of progress. Nevertheless, plenty of opportunity remains for the theorist in the possible interpretation of many individual items, and we have indulged in our share of speculation. Our interpretations now appear to us to be consistent with a place theory that does not employ the principle of simple resonance. We did not begin with this type of theory in mind. The fact that a systematic survey of the field has altered our point of view seems to us to indicate that we were justified in our second reason for undertaking this task: the discovery of the extent to which the field of audition is able to yield a consistent point of view.

One more confession must be made, lest the reader look for what he will not find. Many of the topics of these eighteen chapters have histories which go back far beyond the last decade. To trace these histories adequately, however, would demand many more pages of text than good faith would allow.

us to impose upon the reader. Furthermore, almost all the early psychophysical measurements have recently been repeated under the more favorable auspices of modern electrical techniques. Consequently, out of our list of references, consisting of about 330 titles, more than 280 bear a date more recent than the paper by Forbes, Miller, and O'Connor, who, just ten years ago, first described synchronized nerve impulses in the auditory pathways of the brain. Although we have made no attempt to assemble a complete bibliography, even of recent papers, the appended list of references should provide adequate leads for the student who wishes to pursue a topic to its roots.

Finally, in assembling this review, we have been impressed by the variety of sources from which the facts of hearing are derived. It is characteristic of the science of audition that it ignores the traditional boundaries between the sciences. None of the traditional disciplines nor any of the academic departments of the modern university can claim audition exclusively as its own. The mystery of the ear inspires the psychologist, the physiologist, the otologist, and the physicist alike. Hence, although much of the work recorded in these chapters has been carried out at Harvard University, it is significant that no single laboratory is exclusively responsible for it. There has been active collaboration between the authors, representing psychology and physiology, and members of the departments of otology and physics. Elsewhere the situation is similar. From the Laboratory of Psychology at Princeton University, from the Bell Telephone Laboratories, from the Animal Hearing Laboratory at the University of Illinois, from the Department of Physics in the University of Michigan, from the Department of Psychology at the State University of Iowa, from the Otological Research Laboratory at Johns Hopkins University, from the Government Laboratories of Hungary, from the Telefunken Laboratories of Berlin, from the Laboratories of Physiology and of Psychology in the University of Cambridge, and from many other active laboratories, comes an impressive stream of new discoveries—a fact which means that this book is a current inventory and not a final summary.

The preparation of any manuscript is an arduous task, and authors universally feel indebted beyond expression to those whose helpfulness makes the task bearable. Dr M H Lurie of the Department of Otology has not only collaborated in many of the experiments here recorded, but has kindly provided several photomicrographs of the inner ear. Professor E G Boring read a large part of the manuscript and saved it from many faults. Professor F V Hunt contributed valuable suggestions for the improvement of Chapter I. Mr A H Bernstone devoted much time and talent to the drawing of many of the illustrations. He also read the entire manuscript and contributed to its improvement. Dr A F Rawdon Smith read the proof and suggested valuable modifications. Mr Frank O'Neill's skill as a photographer has aided in the reproduction of many of the figures. Mrs J C Leighton turned our battered first drafts into good copy for the printer, and her skill has been an invaluable asset. To all these friends we are grateful.

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December 28 1937

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- Akademische Verlagsgesellschaft M B H Figs 64, 66, 67
American Academy of Ophthalmology and Otolaryngology Fig 113
American Institute of Electrical Engineers Figs 70, 71, and 75
American Journal of Physiology Figs 110, 128, 130, 131, 147, 148, 149, 150, 153, 156, 157, 158, 163, 164, 165
American Journal of Psychology Figs 68, 74
American Laryngological, Rhinological and Otolological Society Fig 115
American Medical Association Press Fig 22
Annals of Otolaryngology, Rhinology and Laryngology Fig 141
Johann Ambrosius Barth Figs 15, 39, 58, 59, 90, 94, 100, 101
General Radio Co. Table of decibels, Appendix III
Clark University Press Fig 160
Electronics Fig 7
Harvard University Press Quotation on p 17
S. Hurzel Figs 38, 42, 91, 104, 108, 116
The Johns Hopkins Press Figs 136, 137
Journal of the Acoustical Society of America Figs 14, 16, 17, 21, 23, 24, 25, 26, 27, 29, 30, 31, 35, 44, 46, 47, 48, 49, 50, 52, 57, 60, 73, 76, 81, 83, 84, 85, 86, 90, 93, 107, 118, 129, 152, and Table I
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Psychological Review Company Figs 61, 62, 69
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CHAPTER I

THE NATURE OF THE AUDITORY STIMULUS

THE development of the thermionic vacuum tube has revitalized the science of acoustics. Whereas it was formerly necessary to discuss the production, transmission, and recording of sound energy in terms of purely mechanical devices such as tuning forks, organ pipes, strings, sirens, tubes, and reeds, we now treat these problems in terms of electrical and electromechanical systems such as microphones, amplifiers, and loud speakers. Before the advent of electronic instruments, the science of sound had already reached a fullness (Miller, 2)* at the hands of Helmholtz, Lord Rayleigh, and others which made the nature of sound waves well understood. Rudolph Koenig had produced his mechanical masterpieces by which he generated and measured sound waves of various frequencies and forms. Musical instruments had for the most part reached their present stage of evolution, and through the efforts of Sabine a basis for the exact science of architectural acoustics had been discovered. Nevertheless, the principal impediment to further progress in acoustics was the lack of an efficient method for producing and measuring sounds of any desired frequency, intensity, or complexity—a deficiency which has now been removed by the development of electromechanical instruments.

This first chapter will consider the principles of sound, as they bear upon the problem of the understanding and control of the auditory stimulus, and the nature of electromechanical systems, in so far as they are utilized in psychological and physiological investigations.

THE STIMULUS TO HEARING

Any vibratory motion which can be communicated to the auditory mechanism is capable of arousing auditory sensations.

* For explanation of the system of references see p. 457

Stimulation occurs most commonly by sound waves in air, but occasionally by sound waves in water or directly in the bones of the head. Sound waves in any medium consist of rapid vibratory motions on the part of the 'particles' making up the medium. They are called waves because the motion of one particle tends to disturb the adjacent particle, which in turn disturbs the next one, so that a 'wave' of disturbance passes throughout the medium. Thus in the case of air the rapid forward movement of the prong of a tuning fork compresses the air adjacent to the prong, but the elasticity of the air prevents this localized region of compression from being maintained and expansion takes place at the expense of compression of the adjoining region, so that a wave of excess pressure emanates from the prong. In a similar manner, the backward movement of the prong sets up a wave of expansion or diminished pressure. Now, when the prong executes the simplest sort of to-and-fro motion, so as to generate a *pure* tone, its behavior may be described quantitatively in terms of two dimensions: the frequency of its vibrations and the amplitude of its excursions. Likewise we can attribute to the resulting tonal stimulus two physical dimensions, frequency and intensity. Then all the psychological and physiological phenomena which result from stimulation by continuous pure tones can be expressed as functions of these two variables. If a tone is not *pure*, we must add another variable to account for the combinations of frequency and intensity which go to make up the *complex* tone.

To define the stimulus to hearing as *sound* is, of course, a conventional and convenient shorthand. *Sound* in acoustics has come to mean the vibrations of bodies or the transmitted vibrations in media. The rigorous definition of the stimulus to hearing, however, is much more difficult (Boring, 4) and constitutes the subject matter of auditory psychophysics. When we analyze hearing into its various aspects, or attributes, such as pitch and loudness, and ask what is the stimulus to each of them, the answer is not simple. Each turns out to be a complicated function of the dimensions of the vibratory disturbance. Therefore the exact specification of the stimulus to any aspect

of auditory sensation must be expressed in terms of a function of several variables. The stimulus to loudness, for example, can be represented in the form

$$L = f(F, I, C, S)$$

where F is frequency, I intensity, C complexity, and S is a term for the stage along the continuum from the vibrating body through the medium, eardrum, ossicles, etc., at which F , I , and C are measured. This function must satisfy the criteria (1) that equal values of the function produce equal magnitudes of the attribute (pitch, loudness, etc.) and (2) that, where it is possible to construct quantitative scales for the measurement of the attribute, the value of the function is proportional to the magnitude of the attribute as measured on the quantitative scale.

Needless to say, the complete functions cannot as yet be written for the stimulus to every aspect or attribute of hearing. In the chapters which follow we shall, for the most part, hold C and S constant and express graphically the functions between the attributes and their stimuli on plots whose coordinates are frequency and intensity. Hence we shall continue to speak of sound waves as the stimulus to hearing, but we shall understand that the precise definition of the stimulus can be given only after we shall have determined the complete functions relating each attribute to every dimension of the sound waves.

THE DIMENSIONS OF SOUND

The word *dimension* is used here to mean any of what are commonly called the 'physical' aspects of sound, such as frequency, energy, velocity, and phase. These are ways in which sounds may vary, or they are scales in terms of which sounds may be measured. The 'physical' aspects are commonly distinguished from the 'subjective' or 'psychological' aspects of sound, and it is well for our purpose to ascertain upon what operations or concrete procedures such a distinction rests.

The operations involved in the measurement, and hence in

the definition (Stevens, 6), of the energy of sound consist of noting the effect of the sound wave on some other physical system such as a microphone with its associated amplifier and output meter. On the other hand, the operations involved in the determination of the loudness of a sound consist of the direct procedure of noting the effect of the sound on the living organism. The difference between the two procedures lies in the fact that in measuring the 'physical' aspect an observer makes a judgment about a scale reading, whereas in determining the 'subjective' aspect an observer makes a judgment directly about the sound wave itself as it affects his sense-organ. There is perhaps no reason for considering the one type of observational judgment as any more basic or 'physical' than the other, except for the fact that the observations of physics—those which we call pointer readings—constitute the class of human reactions which show the greatest uniformity among individuals and which have therefore been made basic in the exact sciences. The direct observation of the aspects of a stimulus, without the aid of instruments, is made with much less precision. Consequently we can say that the general problem of the psychology of hearing is that of observing the aspects of sound, as it affects the organism directly, and comparing the results with observations of the aspects of sound made with the help of instruments. This chapter deals with the 'physical' aspects of sound and the instruments with which we measure them.

THE FUNDAMENTALS OF SOUND

A convenient aid to the understanding of the physical dimensions of sound is to relate the motion of the vibrating body to what is known as the projection of uniform circular motion. The simplest form of vibratory motion, that executed by the prong of a tuning fork under proper conditions or by a pendulum swinging through a small amplitude, is called *simple harmonic motion*. *Simple harmonic* describes the motion of any body which is displaced from its normal position and then set free, *provided* the force needed to displace the body is proportional to the amount of the displacement. When the force

is proportional to the displacement, the body is said to obey Hooke's law, and the simple harmonic motion which it executes is equivalent to the projection of the motion of a point moving around a circle at a constant rate. Thus in Fig 1 if

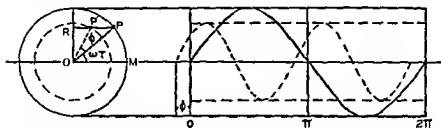


FIG 1 Showing how a sinusoidal wave is generated by the projection of circular motion and how two sinusoidal waves may vary in frequency amplitude and phase

the point P moves around the circle in a counterclockwise direction, its projection on the vertical axis is represented by the point R . As P rotates at a constant rate, R moves up and down the axis of the circle with precisely the same form of motion as that of the prong of the tuning fork. In order to represent this motion graphically we have to spread it out, as shown in the solid curve at the right of Fig 1, the crests represent the regions of compression and the troughs the regions of expansion of the longitudinal sound waves. This curve is obtained by plotting the distance OR against the angle swept by the line OP . If we let ω stand for the angular velocity of P (in radians per second), the angle becomes ωt , where t is the time elapsed since P was at the point M . Now, the distance OR is proportional to the sine of the angle ωt so we speak of simple harmonic motion as sinusoidal motion and represent it by the equation

$$y = A \sin \omega t$$

where y is the displacement OR and A is the length of the vector OP , the distance which is called the *amplitude* of the wave. A is the maximum value y can have at any part of the cycle. The number of times P goes around the circle in one

second is the *frequency*, and since there are 2π radians in a complete circle the relation between frequency F and angular velocity ω is

$$\omega = 2\pi F$$

The total time required for the point P to revolve once around the circle is known as the *period* T , it is the reciprocal of the frequency F .

By *phase* is meant the angle between OP at a particular instant and the same OP at some other instant which is taken as the reference or starting point. If two sinusoidal motions are being considered, we can draw two rotating vectors and speak of their relative phase as the angle between them at some selected instant. Thus in Fig 1 the point P' , rotating around the dotted circle, represents by its projection on the vertical axis a second sinusoidal wave which leads the first by the phase angle ϕ , at the particular instant in question.

If P' rotates twice as fast as P and if it is ahead of P by the angle ϕ , at the instant from which we begin to measure time, the projection of its motion can be represented by the dotted curve to the right in Fig 1. Then, if the vibrating body is executing both motions simultaneously, we can add the dotted curve to the solid curve and obtain a curve which represents the resultant motion of the body. Any number of rotating vectors could be added, with any amplitude and phase, and the resultant wave would become more and more complex. In fact, by adding the waves represented by the proper rotating vectors, any predetermined wave form can be achieved. The word *complexity* is used loosely to designate the number of simple harmonic waves which go to make up a given wave.

Unfortunately, there is no simple scale on which we can order sounds in terms of their dimension of complexity, because two complex sounds having the same component frequencies can differ in terms of the phases and amplitudes of the components. A common procedure is to classify tones in terms of the ratio of the energy in all the frequencies except the lowest

or fundamental frequency to the energy in all the frequencies including the fundamental. Thus a tone with 5 per cent distortion would have 95 per cent of its energy carried by its fundamental frequency, or would be 95 per cent *pure*. More usual, perhaps, is the procedure of defining the percentage of distortion as the ratio of the sound pressures of the harmonics to the sound pressure of the fundamental frequency. This designation of distortion should be used, however, only when the energies of the harmonics are proportional to the squares of their pressures.

For complex tones produced by such generators as a vibrating piano string the component frequencies are in the ratio 1 2 3 4, etc., to each other and are called *harmonic frequencies*, or *partials*. The first harmonic, or the first partial, is the fundamental tone, the others are sometimes called *overtones*.

In our efforts to determine the basic capacities of the ear to discriminate the aspects of sounds, we try to employ pure tones. It is doubtful, however, if we ever succeed in generating tones which have no overtones at all, for even though the vibrating body which produces the sound waves executes simple harmonic motion, the air through which the waves must be transmitted is not perfectly elastic (does not rigidly obey Hooke's law) and some distortion is produced (Fay). This distortion is so small, however, compared to the distortion introduced by the ear itself (see Chapter 7), as to be entirely negligible. Hence, for all practical purposes, we are able to stimulate the ear by what may reasonably be called pure tones.

The word *velocity* as applied to sound usually means one of two things. It ordinarily refers to the velocity of propagation of the sound wave, which determines the time required for a sound produced at one place to be heard at a place some distance away, and which in air is about 331 meters per second. We can also speak of the velocity of the individual particle of air whose motion makes possible the sound wave. On the circle of reference in Fig. 1 the point *R* represents this particle, and the velocity of *R* at any instant represents what is called the particle velocity at that instant. The velocity of the particle is

much smaller than the velocity of the wave, for, even though the particle is in rapid vibration, it moves through such a small amplitude that its maximum velocity is usually of the order of a fraction of a millimeter per second. This maximum velocity occurs at the moment the particle (R in Fig. 1) passes its normal position of rest.

The length of a sound wave is the distance traversed by the sound in the time required to complete one cycle. The *wave length* is equal to the velocity of the wave divided by its frequency. Thus in air the wave length of a 1000-cycle tone is approximately 1 ft, but, since in water the velocity of sound is about four times as great as in air, the wave length of a 1000-cycle tone in water is about 4 ft. A tone of 1000 cycles transmitted to the ear through water would have the same pitch as a tone of the same frequency transmitted through air, provided the two were at the proper relative intensities. This means that the dimension of wave length, which differs so greatly in different media, is of no immediate significance in hearing. It does, nevertheless, become important when one attempts to localize the source of a sound (see Chapter 6).

FORCED VIBRATIONS AND RESONANCE

Whenever a vibrating body is coupled to another body, that is to say, connected to it either directly or by way of some intermediate medium such as air, the motion of the first body is communicated to the second. A loud noise shakes the window panes. A vibrating tuning fork, whose base is pressed against the top of a table, sets the whole table vibrating and thereby intensifies the sound of the fork. These are examples of forced vibrations.

If it so happens that the natural period of the forced body is the same as the period of the first body, the transmitted effect is greatly intensified. This phenomenon is known as *resonance*. Resonance occurs whenever there is impressed upon a body the frequency at which it would vibrate if set in motion and then left to itself. Thus when a tuning fork, in the neighborhood of another fork of identical natural frequency, is struck, vibra

tions are set up in the other fork. A more striking experiment is to hold down the loud pedal of a piano, which frees the strings so that they can vibrate freely, and sing a brief note. This excites those strings whose natural frequencies correspond to the frequencies present in the voice, and a faint replica of the voice is heard after the singing has ceased. The strings which vibrate are said to be tuned to the frequencies of the voice.

All methods of recording and reproducing sound depend upon forced vibrations. The ear itself functions only when forced into vibration, and, according to Helmholtz, the ear's power to discriminate one frequency from another depends upon what may be regarded as a phenomenon of resonance. The importance of these principles requires that we examine them more closely.

In a vibrating system like a tuning fork, three factors determine what the form of the motion will be. They are the mass m , the stiffness s , and the resistance r . If the mass is increased, the vibrations become slower. If the stiffness is increased, they become faster. And if the resistance to the motion is increased, the vibrations die out more rapidly and the system comes to rest sooner. On the assumption of Hooke's law, that the restoring force is proportional to the displacement, it is possible to set up and solve the differential equation which expresses these facts. The solution shows that the frequency of a system for which the resistance is negligible is

$$F = \frac{1}{2\pi} \sqrt{\frac{s}{m}}$$

If the resistance is appreciable, the frequency is decreased slightly and the amplitude of the vibrations falls off according to an exponential curve as shown in Fig. 2.

It is a characteristic of such cases of *damped* vibration that the ratio of the height of the crest A to the height of crest B is the same as the ratio of B to C , of C to D , etc. The constancy of this ratio makes possible a convenient measure of the rate of decay of damped vibrations. This measure is derived from

the fact that the amplitude y of the envelope enclosing the waves in Fig 2 is given as a function of the time t , by the equation

$$y = Ae^{-\frac{rt}{2m}}$$

where A is the initial, or greatest, amplitude of the wave, r is resistance, and m is mass. The natural logarithm of the ratio

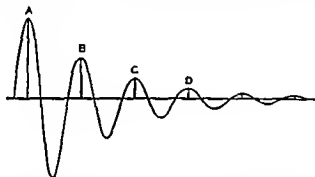


FIG 2 Showing how a damped vibration declines exponentially. The heights of the successive crests bear a constant ratio to one another.

of the height of crest A to that of crest B is known as the logarithmic decrement per cycle. The equation for the logarithmic decrement is

$$k = \frac{rT}{2m}$$

so that, if the resistance r , the mass m , and the period T of the system are known, the logarithmic decrement may be found directly.

The ratio $r/2m$ is known as the *damping factor* of the system. The reciprocal of the damping factor is sometimes called the modulus of decay or the *time constant* of the system. This constant represents the time taken for the amplitude to fall to a proportion of its initial value equal to the ratio $1/e$ or $1/2.718$.

It is important to note that critical damping occurs when

$$r = 2\sqrt{sm}$$

Under this degree of damping, the system comes back from its displaced position to its position of rest without once passing beyond this position. In other words, no free oscillations occur whenever damping is critical or greater than critical.

Now, in the case of forced vibrations, the system is not allowed to come to rest in the manner shown in Fig 2, but is maintained in oscillation by a periodic force. When, however, such a periodic force is suddenly applied to the system, it gives rise to two effects. First of all, on the application of the external force, a type of oscillation is set up which proceeds forthwith to die away in the manner shown in Fig 2. These oscillations are called *transients*. After they have died away there is left a *steady state* response to the external periodic force.

These two effects, a transient and a steady state, are present whenever a system, initially at rest, is set into motion by a continuous periodic force. The time taken for the system to reach the steady state depends, of course, upon the speed with which the transient oscillations are damped out. If the damping is large, the steady state is reached almost at once. Transient oscillations occur also when the external driving force is removed, for the motion of the system must then go through the sort of exponential decay which characterizes all vibrating systems in which resistance is present. The frequency of the transient vibrations is the natural period of the system, the frequency of the steady state vibrations is the frequency of the driving force. Hence it is of great importance in all systems for recording or producing sound, such as microphones and loud speakers and even the ear itself, that the damping be large, for otherwise the transient frequencies would persist long enough to interfere with the frequency of the external force which is being impressed upon the system. What confusion would result if the elements of the ear continued to vibrate long after a note had ceased sounding!

When a periodic force acts upon a system and forces it to oscillate, the amplitude of the oscillations, and hence the velocity of the vibrating particles, depend upon the relation of the

frequency of the driving force to the natural frequency of the system. At resonance the two frequencies are the same, and the velocity of the particles of the forced system is a maximum; but, as the driving frequency departs more and more from the natural frequency of the system, the velocity imparted to the system decreases. By plotting the velocity of the system against the frequency of the driving force we obtain such resonance curves as are shown in Fig 3. Curve *A* represents a system in

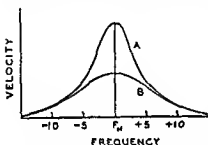


FIG 3 Showing how a resonant system responds to different frequencies. For an impressed frequency F_n which is the natural frequency of the system the velocity attained is maximal. When damping is large the resonance of the system is dull, as shown by curve *B*.

which the resistance is small, and *B*, a system in which the resistance is large. In other words, when a system is highly damped, as represented by curve *B*, the maximal velocity reached at resonance is less and the peak of the resonance curve is much less sharp. Such a system is termed *dull*. Similar curves could be drawn to represent the *amplitude* of a forced system as a function of the driving

frequency, except that the resonance curves for amplitude are not quite symmetrical and do not have their maximum at exactly the natural frequency of the forced system unless the damping is negligible.

According to one view, the analyzing mechanism of the inner ear can be treated as if it were equivalent to a row of resonators, each tuned to a particular frequency. Consequently it is of interest to note that the curves of Fig 3 apply equally well if we consider the abscissa as representing the natural frequencies of a row of little resonators which are being forced into vibration by a single alternating force at the frequency of the middle resonator. The ordinate would then represent the maximum velocity which each resonator would attain, and the duller curve would, as before, represent the case for which the damping is great. (Certain objections which make this

type of theory of questionable value in the treatment of the ear will be considered later (Cf Appendix II)

From a consideration of all the factors which determine the behavior of a system like that hypothesized for the ear, it is clear that nature must make compromises. The ideal of high *selectivity* would demand that each resonator respond vigorously to its own frequency, but only slightly to other frequencies. This requirement would mean sharp tuning and small damping. With small damping, however, it takes a longer time for the system to come to a steady state in response to an applied force, for the initial and final transients tend to persist and interfere. Thus, if the elements in the inner ear were resonators, and were no more highly damped than the strings of a piano when the loud pedal is pressed, we should find ourselves able, perhaps, to distinguish smaller differences in frequency than we can at present, but we should pay for it with extreme annoyance due to sensations which refuse to die out. The obvious failure of auditory sensations to persist is proof of the great damping in the inner ear (see also Chapter 10). Clearly, nature has, for the ear, effected an excellent compromise.

DISTORTION UNDER FORCED VIBRATION

When a simple harmonic force is applied to a system, simple harmonic oscillations are set up, provided the system is *linear*, or, in other words, provided the displacement of the system is proportional to the applied force. For linearity to obtain, it is also necessary that the system be symmetrical in that it moves from its position of rest as easily in one direction as in the opposite. Thus a responding system—an ear, a microphone, a loud speaker, a phonodeik, or a tuning fork—introduces *amplitude distortion* if it is unsymmetrical or does not obey Hooke's law in both directions.

The reason for this distortion can be illustrated by an example. If, instead of the displacement being proportional to the force, we assume it to be proportional to the square of the

force, we can represent the relationship between force and displacement by the 'characteristic' curve in Fig. 4. (In a linear system this would have been a straight line.) Then if we apply a sinusoidal force, as shown at the bottom of the diagram, the resulting displacement will be represented by the curve at the

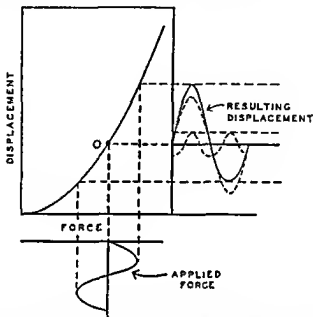


FIG. 4 Showing how a nonlinear relation between force and displacement generates a wave containing harmonic components. A sinusoidal applied force produces a resulting displacement which can be analyzed into the waves shown by the dotted curves.

right of the diagram. This curve is clearly not sinusoidal. In fact, it can be shown mathematically to be equivalent to the sum of the two dotted curves plus a constant factor (which need not concern us). In other words, both the first and the second harmonics are present in the response of a system in which a square-law relation obtains between force and displacement.

In the event that the characteristic curve for the system is not limited to the square law, but requires higher terms for its representation, the equation for the displacement becomes

$$y = a + bf + cf^2 + df^3 + \dots$$

where y is displacement, f is force, and a, b, c , etc., are constants. In this case the higher harmonics are introduced, as can be shown if we substitute for f a sinusoidal force ($f = f_0 \sin \omega t$) and carry out the trigonometric reduction.

The really interesting effect to be obtained from a nonlinear system occurs when two sinusoidal frequencies are applied simultaneously. Here again it can be demonstrated mathematically that the result is a conglomeration of frequencies set up in the system. Thus, if the frequencies m and n are applied together ($m > n$), the resulting motion of the system will be compounded of the frequencies $m, n, (m-n), (m+n), 2m, 2n, (2m-n), (2n-m)$, etc. These component frequencies are not mere mathematical fictions, their physical existence can be shown by means of a system of resonators tuned to each one. If the system is the ear, their presence is confirmed by the existence of the so-called subjective overtones, difference tones, summation tones, etc. (see Chapter 7).

In addition to *amplitude-distortion* we may be concerned in electrical and mechanical systems with *frequency-distortion* and *phase-distortion*. Frequency-distortion occurs whenever a system responds unequally to different frequencies. Thus the curves of Fig. 3 represent a system in which there is frequency distortion, because the response of the system to the resonant frequency is clearly different from that to any other frequency. In the design of an instrument, such as a high quality microphone, in which frequency-distortion is to be minimized, it is necessary, therefore, to avoid having the instrument tuned to any of the frequencies to be recorded. A practical rule (A. H. Davis) is that, to obtain a true record of the relative amplitudes, the natural frequency of the instrument must be 5 to 10 times the highest frequency to be recorded. This insures that the part of the resonance-curve which will be utilized is the relatively flat part far removed from the resonance peak.

Phase-distortion occurs when the response of the system does not preserve the phase relations between the components of the applied force. This type of distortion is not very serious in acoustical systems, because, with slight exceptions (see Chapter

7), the ear is not sensitive to differences of phase between the components of a complex tone

INTERFERENCE

A very simple principle underlies the phenomenon of interference. If two equal forces are applied to a particle from opposite directions they cancel each other and the net effect is *nil*. Thus, if two tuning forks of the same frequency are sounded in such a way that a wave of compression from each of them reaches a point midway between them at precisely the same instant, their effects on a particle at that point are canceled. But, if a wave of compression from one fork coincides with a wave of expansion from the other, the effect on the particle is doubled. Now, if the frequencies of the two forks differ by a slight amount—2 cycles, let us say—their waves will cancel each other the part of the time that they are out of phase, and reinforce each other the rest of the time when they are in phase. Consequently, a person listening to the forks experiences a periodic waxing and waning of the sound at a frequency of 2 per second. Such periodic changes in intensity are called *beats* (see Chapter 9).

It is not necessary, however, to have two sources of sound in order to demonstrate interference. Indeed, whenever a tone is produced inside a room, the waves which are reflected by the walls return to interfere, and diminish or reinforce the sound, depending upon the phase relations between the direct and the reflected waves. This phenomenon gives rise to many serious problems in acoustics. Perhaps the most drastic consequence of interference due to reflected waves is that it becomes impossible to know the intensity of a tone at a given point in a room merely by knowing the intensity of the tone at the source. In free space sound waves behave as light waves, the intensity decreases inversely as the square of the distance from the source, but, the moment it becomes possible for a wave reflected by some surface or object to reach the point at which the intensity is being measured, the simple relationship of the square law no longer holds. Since almost all smooth, rigid wall surfaces

are even more efficient reflectors of sound than mirrors are of light, the difficulties in the way of predicting the behavior of sound in a closed room are comparable to what they would be for light if every surface in the room were a polished mirror.

A continuous steady tone released in a room quickly sets up a pattern of *standing waves*, that is to say, a pattern of cancellations and reinforcements which results in the intensity of the sound being very different at different places in the room. By moving the head slightly when a continuous tone is sounding in a room, marked changes in loudness are readily experienced.

Among the first to call attention to the problem of interference was W. C. Sabine. He wrote the following:

In order to show this [the effect of standing waves] in a definite manner, I have measured the intensity in all parts of a certain laboratory room. It was found, near the source, even at the source itself, the intensity was in reality less than at a distance five feet from the source. And yet the clever experimenter Wien, and no less skilled psychologists Wundt and Münsterberg have assumed, under similar conditions, the law of variation of intensity with the inverse square of the distance.

Not only do the walls reflect sound in such a way that it becomes many times more intense than it otherwise would be, but even the total quantity of sound emitted by the source itself may be greatly affected by its position with regard to the interference system of the room.

It is thus necessary in quantitative research in acoustics to take account of three factors: the effect of reflection by the walls on the increase in the total intensity of the sound in the room, the effect of interference in greatly altering the distribution of this intensity, and the effect of the reaction of the sound vibrations in a room upon the source itself.

In choosing a source of sound, it has usually been assumed that a source of fixed amplitude was also a source of fixed intensity, e.g., a vibrating diaphragm or a tuning fork electrically maintained. On the contrary, this is just the sort of source whose emitting power varies with the position in which it is placed in the room [because, if the source is placed at a point of reinforcement in the pattern of standing waves, its vibrations are more effective in imparting energy to the surrounding medium].

The remedy to be applied when it is desired to stimulate the

ear in a closed room and at the same time maintain adequate control of the intensity of the sound is either to prevent, by the use of earphones, the sound from running loose in the room, or to treat the walls with an absorbent material which will prevent reflection. This procedure is analogous to painting black the walls of a room in which light is to be used for experimental purposes. By the proper selection of materials and the exercise of care in placing the source and the listener, the amount of reflected sound reaching the listener can be made negligible compared to that which reaches him directly. Nevertheless it is impossible completely to duplicate the conditions of 100-per cent absorption which characterize free space.

The effect of increasing the absorption of the walls of a room is to decrease the apparent average intensity of the sound from a given source, because the intensity which normally results from the sound's reflecting back and forth from wall to wall for a period of time after it has left the source is absent. Likewise, when the source is suddenly extinguished, the sound dies out sooner. Under these conditions we say that the *reverberation time* of the room has been decreased. Reverberation is probably the most important single concept in the new science of architectural acoustics, for the satisfactoriness of an auditorium as a place for listening to speech and music is greatly dependent upon the length of time a sound persists after it has left the source. This time must be neither too short nor too long.

Caution should be voiced concerning the use of tubes for the purpose of conducting sound to the ears, for standing waves are set up as readily in tubes as in rooms. Perhaps the most satisfactory method for conducting sound waves by tubes is to employ the equivalent of a tube of infinite length and use a short side tube (short compared to wave length of the sound) to conduct the sound from the main tube to the ear. A practical 'infinite tube' can be obtained by taking about 20 ft. of garden hose and lining it throughout its length with some absorbent material, such as mohair. Strange as it may appear, if an unlined tube is left open at the end reflection will occur

THE ANALYSIS OF SOUND

As we have already seen, simple harmonic motions can be added together to produce a complex motion. What is more important, however, is the fact that any complex periodic motion can be analyzed into a series of simple harmonic components. The truth of this statement can be demonstrated mathematically by *Fourier's theorem*. For our purposes this

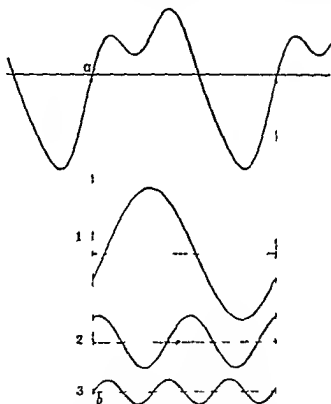


FIG. 5. Showing how a complex wave may be analyzed into Fourier components in harmonic relation (Miller 1)

theorem may be stated as follows: given any periodic motion having a fundamental frequency n , the same motion can be reduced to one particular set of simple harmonic motions of suitable amplitudes and phases whose frequencies are n , $2n$, $3n$, $4n$, etc. Thus the tone emitted from a violin may appear on an oscillograph as the upper curve in Fig. 5. This curve can then

be analyzed into the components represented by the curves numbered 1 to 3. In general, the greater the number of components taken, the more faithful is the reproduction of the original curve when the components are put back together. Several ingenious mechanical devices have been developed both for discovering the components of the wave, once its form is known, and for synthesizing the components to recover the original wave form.

An analysis of a sound wave could be made directly by means of a series of resonators (such as Helmholtz's resonators) each tuned to a different frequency. Each component frequency of the complex sound would then activate only that resonator to which it is tuned, and the composition of the sound could be determined by noting which resonators respond and how much. The obvious disadvantage of this method is the inconvenience of providing a sufficient number of resonators adequately to cover the range of frequencies. Consequently it is little used in practice.

The ear, however, does its analyzing *as though* it contained just such a series of resonators (see Chapter 10). As a result, the ear is in general able to detect the presence of component frequencies in a sound wave and to identify their pitch provided they are not too numerous or too faint. This interesting fact is known as *Ohm's acoustical law*. The mechanical and physiological mechanisms underlying this law will be dealt with later.

Since most of the sounds with which we are concerned in modern acoustics are either produced electrically or can be readily converted into an electric current by means of a microphone and amplifier, the analysis of sound can be reduced in practice to the analysis of electric currents. Electrical wave-analyzers have the important advantage that continuous tuning can be employed so that every component of the wave can be detected and measured. Many types have been developed (Hall, 2). A typical commercial analyzer consists, functionally, of two parts. The first is a voltmeter tuned to respond to a single frequency only, the second is a means of changing this tuning so that any desired frequency in the audible range

can be measured The operation of an analyzer will be discussed later (p 39)

FREQUENCY AND ITS MEASUREMENT

Frequency is the measure of the number of times per second that a vibrating particle executes a complete cycle, as illustrated by the circle of reference (Fig 1) Hence, frequency has come to be measured in cycles (per second) rather than in double or single vibrations, as was formerly the custom A cycle is two single vibrations or one double vibration Contrary to what is customarily stated in textbooks on physics, frequency is not synonymous with pitch Pitch is determined by a direct observation of an aspect of sound as it affects the ear, whereas frequency is an observation of an aspect of sound which we are obliged to perform with the help of instruments Such instruments are known as tonometers, or frequency meters

The mechanical types of tonometers which have been devised for the measurement of frequency are varied and ingenious They are based in general upon the principle of sounding a tone of known frequency, which is nearly the same as that of the frequency to be measured, and determining the difference between them Datta lists fifteen schemes which have proved more or less successful Their chief limitation lies in the fact that they are generally useful only for the measurement of low frequencies

In modern acoustics—as in radio engineering—electrical methods have come into use for the measurement of frequency because of their convenience and the wide range of frequencies to which they are adequate Since most of the tones used in psychophysiological studies are produced by electrical generators, their frequency can be determined by measuring the frequency of the electric current which activates the generators Thus, in a simple commercial frequency meter, the electric current to be measured is led to an electric circuit (a bridge) consisting of resistances and capacitances, so arranged that, when their values are properly adjusted, the circuit is tuned to the frequency of the current Then, where the values of the re

sistances and capacitances are known, the frequency can be calculated. In practice, however, it is customary to calibrate the meter so that the frequency can be read directly from a dial.

The calibration of modern frequency meters is made in terms of some primary standard of frequency. A typical standard consists of an electrical oscillator to generate an electric current at a frequency of approximately 50 000 cycles. This frequency is fixed by the characteristics of a vibrating bar of quartz, which is made to vibrate by the electric current. In addition there is another oscillator, known as a multivibrator, which generates an electric wave that is rich in harmonics. The frequency of the multivibrator is adjusted until some one of its harmonics coincides with the frequency of the quartz oscillator, and then, since the other harmonics are in fixed ratios, their relative frequency is known. From a standard of this sort it is possible to obtain frequencies equal to any of the harmonics of the multivibrator. The accuracy of these frequencies is better than 1 part in 1 000,000.

One of the harmonic frequencies, 1000 cycles (very closely), is then made to drive a synchronous clock, similar to the electric clocks used in the home, except that it is driven by a current of higher frequency. The clock generates a sharp pulse of current every thousand cycles (once a second), which can be compared with the radio time signals sent out by an observatory. Thus the frequency of the current driving the clock can be determined. Briefly stated, this method consists essentially of running an electric clock by means of a frequency known only approximately and comparing the time told by the clock with the time determined by an observatory. The difference, if any, measures with extreme accuracy the amount by which the unknown frequency differs from the frequency for which the clock was designed (1000 cycles in this case). Through the careful application of these methods, the frequency of an electric current, which formerly was known with much less accuracy than such circuit constants as electrical resistance, has come to be the most exactly determined constant of all.

Once a single frequency is known, other frequencies which

are in harmonic relation to it can be determined with great precision and convenience by means of a cathode ray oscillograph (see p 40) If the known frequency is impressed upon the horizontal plates of the oscillograph so as to deflect the beam of electrons back and forth in the horizontal plane, and at the same time a frequency is impressed upon the vertical plates, the result is a geometrical pattern, known as a Lissajous' figure,

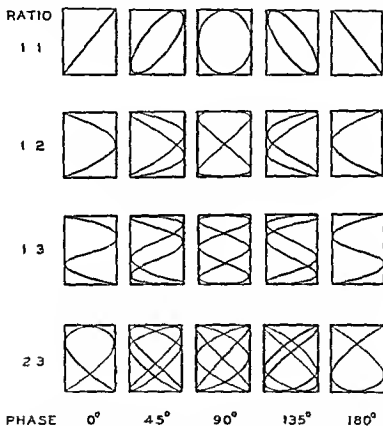


FIG. 6 Lissajous figures obtained by a pair of sinusoidal motions—one vertical the other horizontal—whose frequencies are in certain ratios and phase-relations. The ratios express the relation of the frequency of the vertical to that of the horizontal waves

which remains stationary provided the two frequencies bear some simple numerical relation to each other. Thus, if the two frequencies are identical, a circle, an ellipse, or a straight line is obtained, depending upon the relative phase of the two waves

If they are in the ratio 2:1, the figure is a semicircle, or figure eight. If the frequencies are not quite in the proper ratio, the figure changes at a rate which can be counted when the divergence is not too great. Typical Lissajous' figures are shown in Fig. 6.

When it is desirable to record frequencies which are continuously varying, another type of meter can be used (Hunt). This meter incorporates an ingenious method of indicating directly on the dial of an ammeter the frequency of an electric current at any instant. Each time the alternating current crosses the zero axis (reverses sign) it trips a pair of discharge tubes and allows a pulse of current of predetermined size to flow through an ammeter. Then, since all the pulses are the

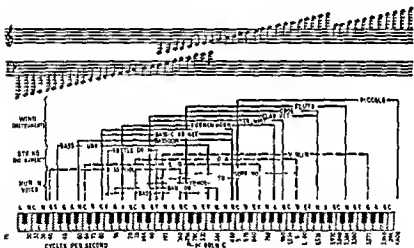


FIG. 7 The relation between the musical scale and frequency (After Henney)

same size, the reading on the ammeter is directly proportional to their number per second, and hence directly proportional to the frequency of the current. Thus, simply by calibrating its dial, the ammeter becomes a direct reading frequency meter.

The musical scale is, of course, a scale of frequency. Thus Fig. 7 shows the frequency of the notes of the musical scale, and the range of frequencies covered by common musical instru-

ments and the human voice. The particular scale illustrated here is the one in which all the C's are powers of 2. This scale is not, however, in general use by musicians. The notes of the scales which are commonly used differ in frequency by only a few cycles from the scale in Fig. 7.

INTENSITY

The use of the word *intensity* to denote an aspect of sound has perhaps entailed more ambiguity than any other single practice in acoustics. It is important, therefore, that we clarify the meaning of the word and adopt some standard, unambiguous usage of it.

First of all, we must understand that intensity is not synonymous with loudness. Intensity, like frequency, is one of the physical aspects of sound which we are able to observe only with the aid of instruments. Loudness, like pitch, is one of the aspects which we observe directly. Furthermore, there is no one-to-one correlation between pitch and frequency nor between loudness and intensity.

Although the definition of frequency is a relatively simple matter, the definition of intensity is not so readily achieved, for reasons which we shall discover. Perhaps for our purpose a satisfactory general definition of the intensity of a plane sinusoidal sound wave in air is as follows. Intensity is the other variable besides frequency whose value must be specified in order completely to determine the sound wave. This is equivalent to saying that sound is two-dimensional and that intensity is one of the dimensions. There are several alternative ways of specifying the second variable once the frequency has been determined. In other words, intensity is a generic term designating a class of alternative ways for specifying a physical aspect of sound.

As we have seen, the propagation of a sound wave in air involves rapid alternating displacements of the air particles, and is associated with oscillatory changes in the pressure and velocity of the air. In addition, the propagation of the wave entails a transfer of energy through the air, and ends by exerting a tiny

which vary sinusoidally, it is customary to take as the measure of the quantity its root mean square value. A straight average of a sinusoidal function would, of course, be zero, for the function is below the axis as much as it is above the axis. By squaring all values of the function before averaging, the negative sign of the part below the axis is eliminated. If the function is strictly sinusoidal, the rule is that the root mean-square value is the maximum value (the amplitude) divided by the square root of 2.

Care should be taken not to confuse the alternating pressure of a sound wave with the radiation pressure, which is the pressure exerted by the wave on an object which it strikes. This radiation pressure is unimportant, practically, as a measure of intensity. It is, in fact, directly proportional to the energy of the sound wave.

Energy is expressed in two ways, either as the average energy per unit volume or as the average rate of flow of energy through a unit area. The rate of flow of energy is simply the average energy per unit volume times the velocity of sound. The equation for the rate of flow of energy J is usually written

$$J = \frac{1}{2} \rho_0 c A^2 \omega^2$$

where the symbols have the same meaning as in Fig. 8. Hence, the energy of a sound wave is proportional to the square of the frequency times the square of the amplitude (of the particles). The pressure of a sound wave, however, is proportional to the frequency times the amplitude, as shown in Fig. 8. It follows, then, that the energy is proportional to the square of the alternating pressure, or in symbols

$$J = \frac{p^2}{\rho_0 c}$$

where p stands for the root mean square value.

It must be emphasized that these relations between displacement, velocity, pressure, and energy obtain for a plane progressive sound wave. In many situations, especially where standing waves occur, the energy is not proportional to the square of the

pressure, and under these circumstances the various measures of the strength of a sound-wave cannot be used indiscriminately. This consideration has led, in acoustics, to the adoption of a definition of *sound-intensity* in terms of the rate of flow of energy through a unit area of the medium (Frederick). This definition (see Glossary) should be used whenever the energy is not proportional to the square of the pressure of a sound-wave.

THE DECIBEL

The difficulty of deciding upon the best measure of intensity is somewhat obviated by the modern convention of expressing intensity as a ratio rather than as an absolute magnitude. The need for this procedure grew out of the problems involved in the transmission of electric waves over networks—a major problem of the telephone-engineer. Thus, when an impulse is sent over a wire, its intensity diminishes as it progresses, and at the receiving end it is smaller than it was at the sending end. What was needed was a convenient method of expressing the magnitude of the impulse at the terminus in terms of its magnitude at the beginning, and the logarithm of the ratio of the energy at the terminus to the energy at the beginning was taken as the measure. In honor of the inventor of the telephone, the logarithm (to the base 10) of this ratio defines the number of *bels* comprising the ratio. In practice it is more common to measure the ratio of two energies in *decibels* (abbreviated db). A decibel is one-tenth of a bel

The number of decibels is thus defined as 10 times the logarithm of the ratio of two energies or powers, but decibels can also be used to designate the ratio of two pressures, velocities, voltages, currents, etc., which are related to the flow of energy by a square law. If N represents the number of decibels, we have . . .

$$N = 10 \log \frac{E_1}{E_2} = 20 \log \frac{p_1}{p_2}$$

where the E 's are energies and the p 's are pressures. Since the decibel is defined in terms of the ratio of two energies, care must

be taken in applying the formula to the ratio of two currents or two voltages. The currents or voltages must always be measured across the same impedance or the formula does not hold. In practice, we are usually interested in comparing two voltages impressed upon the same loud speaker, or other device, and in this case we can properly say that the number of decibels between the two voltages is 20 times the logarithm of their ratio.

Properly used, the decibel has several advantages. Since it is a logarithmic unit, it is convenient for the representation of the great range of intensities encountered in acoustics. The ear can support a sound whose energy is about a million million times the least energy it can detect. This huge difference can be expressed as 120 db. A second advantage is that we can add decibels instead of multiplying. Thus if we have two amplifiers in series and each of them amplifies the voltage tenfold we add 20 db for each amplifier and obtain the result that the total amplification is 40 db. A third advantage is that the decibel scale provides what is essentially a common denominator for expressing intensities. In other words, if, from a certain reference point, the intensity of a plane progressive sound wave is increased 60 db, as determined by measurements of energy, it has also been increased 60 db as determined by measurements of pressure or particle velocity.

Clearly the measurement of sound intensity in decibels presupposes a standard or reference intensity, for the decibel scale must always represent the relation of one intensity to another. A common point of reference is the threshold of hearing—the least energy necessary to arouse an auditory sensation. Where possible, however, it is better to measure intensity in decibels above the value which has been proposed as the reference intensity, namely, 10^{-16} watt per square centimeter (see Glossary). (The watt is a measure of the rate of flow of energy.) For a plane sound wave in air, this intensity is approximately equivalent to the root mean square pressure of 0.0002 dyne per square centimeter, or a particle velocity of 0.000005 cm per sec, and is reasonably close to the average threshold of hearing for a 1000-cycle tone (see Chapter 2). A scale representing the ap-

proximate intensity of familiar sounds in decibels above the reference intensity is shown in Fig 9

Decibel scales will be used freely in the later chapters, and our ability to grasp their meaning will be greatly aided if we keep certain points in mind. Most important, we should remember that the decibel scale is a logarithmic scale expressing the magnitude of the ratio between two quantities. Then, as a practical matter, it is well to remember certain useful equivalents. When we refer to sound pressure, or to the voltage applied to a loud speaker, a tenfold increase means the addition of 20 db and a twofold increase means the addition of very nearly 6 db. By remembering that every time we multiply the

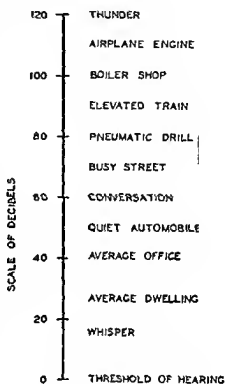


Fig 9 Loudness-levels, in decibels, of various common sounds

pressure by 10 we must add 20 db and every time we multiply by 2 we must add 6 db, it is relatively easy to find the approximate number of decibels corresponding to any pressure ratio. For example, a pressure increase of eightyfold is an increase of $10 \times 2 \times 2 \times 2$ or the addition of $20 + 6 + 6 + 6$ db, which equals 38 db. (For a table relating pressure ratios to decibels see Appendix III.)

THE MEASUREMENT OF INTENSITY

Drysdale has reviewed the difficulties which have tended to thwart the development of acoustic measurements and instruments. He makes the following points:

1. Acoustic power is an extremely minute quantity, the

power usually available for measurement is but a small fraction of a microwatt (One microwatt = 10 ergs per second)

2 Acoustic power is not generally transmitted along definite paths, like electric currents in conductors, but is radiated in all directions so that only a certain portion of the total power emitted by the source can be picked up

3 The wave length of most audible tones is of the order of a few inches to a few feet, and is therefore neither very large nor very small compared with the dimensions of most recording instruments. On this account the reactions of the instrument on the waves are extremely troublesome, and it becomes difficult to obtain a true sample for measurement

4 Owing again to the size of the wave length, interference phenomena and reactions between source and receiver are likely to be embarrassing

5 The construction of surfaces which will completely absorb all sound which reaches them is difficult, if not impossible. Hence, reflections and standing wave patterns arise to cause unsuspected errors

These points, although serious, are not insurmountable. They represent, however, stubborn facts which every acoustical engineer must face when he sets out to measure sound

Lord Rayleigh gave us what is undoubtedly the best practical method for the absolute measurement of sound intensity. He observed that a light disk suspended in a sound field tends to set itself at right angles to the direction of the sound. Consequently it becomes possible to develop a formula relating the force needed to turn the disk (the turning moment) to the rate of flow of the air past the disk. The turning moment is proportional to the mean square velocity of the air particles. A Rayleigh disk, properly constructed and employed, can be used as a standard in terms of which other instruments, such as microphones, can be calibrated

Practical measurements of sound intensity in the laboratory are nearly always made by means of a calibrated microphone that is to say, a microphone for which the relation between the current generated and the pressure on the diaphragm has been

determined for all frequencies to be measured. When the relation of current to pressure is known, the microphone is said to have a *pressure-calibration*. Then, by placing the microphone in a sound field and measuring the current generated, we can compute the value of the sound pressure at the face of the microphone.

A complication arises when we place an ordinary microphone in a sound field, because the presence of the microphone tends to distort the field, and the pressure on the diaphragm is not what the pressure of the sound was at the same place before the instrument was placed there. To obviate this difficulty, we resort to a *field-calibration*, that is to say, we determine the intensity of the field, perhaps by means of a Rayleigh disk, and then insert the microphone and determine the current generated. Then, by placing the microphone in an unknown field, properly oriented with respect to the direction of the sound wave, we can determine the intensity which would exist in the unknown field at that point if the microphone were not there.

In an effort to obtain a microphone which will not distort the sound field and which will give the same response regardless of the direction of the sound wave, many types of instrument have been developed. In order not to distort the field in any way, the microphone must be made infinitely small, but the ideal of a nondirectional microphone—one which responds equally well to sound from all directions—can be achieved, in practice, by a properly designed baffle around the microphone (Marshall).

Similar considerations apply to the distortion and directionality consequent upon placing the head in a sound field. Thus, in general, two procedures are possible for the measurement of such items as minimum audible intensities. The intensity of the field may be determined without the presence of the human observer, and this intensity taken as the intensity of the stimulus. In this case the head must be oriented in some standard manner towards the source of sound. Or the intensity of the sound at the eardrum of the observer may be determined

after he is in the field, a procedure which involves certain difficulties, however (see Chapter 2)

THE ELECTRICAL ANALOGY

Throughout the preceding discussion, attention has frequently been called to electrical devices and methods. Not only does the modern science of acoustics owe its recent advances to the invention of practical instruments for the production and measurement of sound waves, but the theory of sound itself has been extended with the aid of the methods of analysis which were originally developed to deal with electrical phenomena. A mechanical or acoustical system is composed of elements whose relationships can be treated by the same form of differential equations which are basic to the analysis of electric circuits. Each variable of the equations in the theory of circuits has its analogue in a variable of the corresponding mechanical equation. The conventional analogy between some of these variables is as follows:

MECHANICAL		ELECTRICAL
Force	resembles	Emf
Velocity		Current
Mass	"	Inductance
Frictional resistance	"	Resistance
Compliance (i.e., $1/\text{stiffness}$)	"	Capacity
Displacement	"	Quantity of charge

An alternative analogy has been suggested by Firestone, who points out some advantages not possessed by the conventional analogy. In other words, there is nothing sacred or in any sense fundamental about the identification of mass and inductance, for we could equally well construct the equations in such a way that mass and capacity would play analogous roles. Nevertheless, the use of these analogies—conventional or otherwise—has led to many elegant treatments of acoustical problems, and the student of acoustics finds the study of circuit theory an essential element of his training. Thus the marked progress in the acoustics of absorbent materials, in the design

of acoustic filters, in the construction of all sorts of electroacoustic transducers for the conversion of sound into electric energy, and vice versa, has hinged upon the development and use of such functions as acoustic impedance, which, like electric impedance, is a concept of great utility and power. For an extensive application of these notions, the reader is referred to modern works on acoustics.

ELECTRICAL APPARATUS

The purpose of this section is to sketch the characteristics of the electrical apparatus most commonly encountered in modern experiments in hearing. The descriptions are not of particular experimental set ups, but apply to what might be called an idealized set of equipment. All such apparatus has been used in the studies to be reported in later chapters.

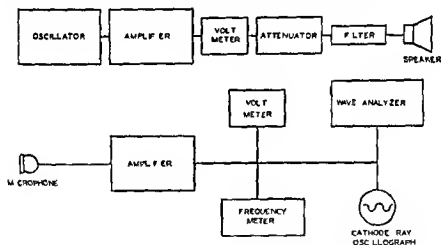


FIG. 10 The elements of an experimental set up designed to produce and record any desired tones.

We may begin by referring to Fig. 10, which is a schematic diagram of an ideal arrangement for the investigation of psychophysiological acoustics. The upper system is for the generation of pure tonal stimuli at any desired frequency and intensity. The lower system is for the recording, measuring, and analyzing of sound. We shall consider each element in turn.

It is perhaps desirable to consider first the *amplifier*, for oscillators are essentially a special type of amplifier. The core of the amplifier is the vacuum tube. The vacuum tube, called in England by the suggestive name *valve*, is simply a device in which a small electrical potential is able to control the behavior of a large current. It is like a valve whose opening is regulated by a force which is very small compared to those which its opening may bring into play. The vacuum tube is connected in the circuit as shown diagrammatically in Fig. 11. The filament F is heated by current from the battery A . The heating

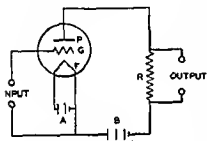


FIG. 11 The elements of a vacuum tube amplifier

so agitates the electrons in the filament that some of them fly off into the surrounding space, and, since they are negative charges, they are drawn towards any body possessing a positive charge. Such a body is the plate P , which is positively charged by being connected to the battery B . Now, the stream of electrons which flows from the filament (cathode) to the plate (anode) is very sensitive to any charge it might meet on the way. Consequently, a perforated grid G is placed between the filament and the plate, and any charge induced on the grid is effective in determining the number of electrons that are able to get across. Then, when the voltage to be amplified is impressed on the grid, and makes the grid swing negative, the electrons are hindered in their passage, when it makes the grid less negative, the electrons are accelerated. The result is that each change in the grid voltage is reflected in the current through the resistance R and hence in the voltage across R . This output voltage can then be led to the grid of another tube, and so on until the original voltage has been amplified millions of times. There are numerous ways of coupling one stage to another, each with its particular advantage for certain types of service. For most work in acoustics the ideal amplifier is one

so agitates the electrons in the filament that some of them fly off into the surrounding space, and, since they are negative charges, they are drawn towards any body possessing a positive charge. Such a body is the plate P , which is positively charged by being connected to the battery B . Now, the stream of

which amplifies all frequencies equally well, and does so without introducing amplitude-distortion due to nonlinearity. The latter ideal is met in an amplifier, as in a mechanical system, when the response of the system (output voltage) is proportional to the impressed force (input voltage) symmetrically in both directions. If the ideal is not met, harmonics are introduced into the output.

An *oscillator* is simply an amplifier in which there is provision for leading back to the grid circuit a small part of the power in the output circuit. The part led back, provided that it arrives at the grid circuit in the proper phase, is then amplified again to produce more power in the output circuit from which another small part can be led back to repeat the process all over again. The phase and the frequency at which the impulses are sent back to the grid circuit to be reamplified are determined by a *tuned circuit* that is, a circuit consisting of inductance and capacity adjusted to give it the desired natural frequency. This natural frequency can then be conveniently regulated simply by changing the capacity of the circuit.

In order to obtain any frequency in the audible range by merely turning the dial of one variable condenser, it is necessary to resort to the method of *beat frequencies*. Two oscillators are constructed with natural frequencies of the order of 100,000 cycles, and the frequency of one of them is controlled by a variable condenser. The outputs of both oscillators are led to a single mixer tube where they interact to produce beats. The beats, whose frequency is equal to the difference between the frequencies of the two oscillators, are then amplified and led to the output of the instrument. Thus, if one oscillator is tuned to 100,000 cycles and the other to 101,000 cycles, the frequency obtained from the output will be 1000 cycles. The two high frequencies do not appear in the output because they are filtered out by the proper arrangement of the circuits. An alternative name for this type of oscillator is *heterodyne oscillator*.

The third element of our producing system might well be a *voltmeter* to measure the output of the amplifier and provide assurance that its behavior is constant.

Next, in order to impress any desired voltage on the loud speaker, an *attenuator* is introduced. An attenuator is a network of resistances designed to reduce the voltage and at the same time keep the other circuit constants, such as impedance, unchanged. An attenuation network is usually constructed in sections, each section designed to decrease the voltage by a certain number of decibels. Then, simply by adding in or taking out sections, any degree of attenuation can be obtained.

If the output of the amplifier contains undesired harmonics, they can be eliminated by a properly designed *filter*. A filter is a network which offers more impedance to the passage of some frequencies than others. The elementary notion of a filter can be illustrated if we imagine an inductance placed across the output of our amplifier. Now, since an inductance offers small impedance to low and large impedance to high frequencies, the low frequencies would be shunted through the inductance, and only the high frequencies would be passed on to the speaker. On the other hand, if a condenser is placed across the output, it shunts out the high frequencies and lets the low frequencies pass by. So, by the proper combinations of inductances and capacitances, filters can be designed to pass any desired frequencies and stop all others.

An analogous theory can be applied to the construction of tubes which have openings and side tubes that filter certain frequencies out of a sound wave. These are called acoustic filters (Stewart, 5).

Finally, we arrive at the electroacoustic *transducer*. This may be any sort of loud speaker or receiver. So many varieties have been developed—magnetic, moving-coil, thermoelectric, piezoelectric, condenser, eddy current, ribbon, etc.—that their description cannot be undertaken here. The ideal high-quality generator of sound is one which responds equally to currents of all frequencies in the audible range. Another requirement, and one which is realized in most types of instrument, is that the alternating pressure of the sound wave generated be proportional to the impressed voltage. When this is the case, we have simply to measure the voltage, and we have a relative measure

of the sound intensity. This relationship is true, of course, only when we release the sound in an absorbent room where interference phenomena are absent.

Next we shall consider the recording system. A *microphone* is essentially a receiver which is made to work backwards. It converts sound-energy into electric energy. As might be expected, there are about as many types of microphones as there are receivers, and in general the same ideals must be met by a high-quality instrument, namely, uniform response at all frequencies and a response (voltage output) proportional to the pressure (or velocity) of the sound wave. As we have previously noted, an additional requirement might be that the microphone be nondirectional and produce negligible distortion when it is placed in a sound field.

From the amplifier, which amplifies the response of the microphone, the current may be led to one or all of the instruments indicated in Fig. 10. The voltmeter would permit us to determine the intensity of the sound, provided the microphone had been calibrated and we knew the gain of the amplifier.

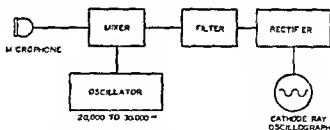


FIG. 12. The elements of a recording wave analyzer.

The *frequency meter* would determine the frequency of the sound. If the sound were complex and it was desired to know its frequency composition, a *wave-analyzer* would be needed.

An automatic *analyzer* (Hall, 1) is shown schematically in Fig. 12. A microphone picks up the sound wave to be analyzed and delivers it as an electric wave to the mixer, which performs the same function as the mixer in the beat frequency oscillator. The other wave led to the mixer comes from an oscillator designed to produce frequencies between 20,000 and 30,000 cycles

The mixer then produces a frequency which is the difference between that of the sound at the microphone and that coming from the oscillator, and sends it on to a filter (a magnetostrictive rod) tuned very sharply to 20,000 cycles. No other frequency can pass this filter. Therefore, nothing gets through to the rectifier unless the difference between the frequency of a component of the wave from the microphone and the frequency from the oscillator is 20,000 cycles. Thus, when the microphone picks up 500 cycles, the filter passes a wave only when the oscillator produces a frequency of 20,500 cycles. The trick then is to make the oscillator sweep from 20,000 to 30,000 cycles continuously, and note when a frequency gets through the filter and is recorded on the cathode ray oscillograph. The dial of the oscillator can be driven by a motor and the response on the oscillograph can be recorded on a moving film, so that a permanent record is made of the intensity of each component frequency in the wave picked up by the microphone.

The purpose of a cathode ray *oscillograph* is to reproduce in a visual pattern the characteristics of an electric wave. Fig 13

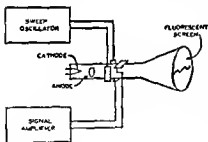


FIG 13 The elements of a cathode-ray oscillograph

is a schematic representation of the essential parts of a cathode ray oscillograph. One type consists of a glass tube, evacuated to a high vacuum, in the small end of which is a filament (cathode) which, upon heating emits electrons. These electrons are drawn violently forward by an anode which bears a positive charge

of a thousand volts or more. In the anode is a small hole through which some of the electrons pass with sufficient velocity to carry them on to the large end of the tube. Thus a small stream of electrons is shot from one end of the tube to the other, like water from a garden hose, and each time an electron strikes the large end of the tube, which is coated with a fluorescent material, it makes a little 'splash' of light. Hence

one sees a bright spot where the stream strikes the fluorescent screen. Now, in order to obtain a pattern, it is merely necessary to deflect the stream by passing the electrons between a pair of metal plates on which there is an electric charge that can attract or repel them, depending upon the sign of the charge. Two pairs of plates—vertical and horizontal—permit deflection of the beam in both directions.

In order to obtain a true representation of an electric wave, it is customary to employ a device known as a sweep circuit. A sweep-circuit impresses on the vertical plates a potential that grows at a constant rate and pulls the spot horizontally across the face of the tube. Then suddenly the potential falls to zero and the spot flashes back to the other side of the screen, where it starts another trip across the tube at a constant speed. The action of a sweep-circuit depends upon the alternate charging and discharging of a condenser through a gaseous discharge tube. Now, with the spot traveling uniformly across the face of the tube, it becomes a simple matter to impress the potential to be studied (the signal) upon the horizontal plates and thereby make the spot move up and down at the same time. The net result is a true picture of the electric wave.

The study of electric and acoustic phenomena has been tremendously aided by the cathode ray oscillograph, and it is perhaps no exaggeration to say that much of the recent work on the physiology of hearing would have been impossible without it.

CHAPTER 2

THE SENSITIVITY OF THE EAR

THE absolute sensitivity of the ear is determined by the minimal energy or sound pressure needed to excite a sensation of hearing. This amount of energy is called the *threshold value*. In addition to the various practical problems which arise when we set out to determine the threshold of hearing, such as the apparatus and procedure to be used, two fundamental questions must be decided: first, the form of energy, electrical or mechanical, that we shall take as the stimulus, and, second, the point in the long, continuous process from the original generator of the energy to the final experience of tone at which we shall choose to measure the energy. Obviously, very different results would follow from measuring at, say, the generator and at the eardrum, or even in the auditory nerve. Different experimenters have selected different points for the measurement of the least audible energy, but in general, for the determination of the threshold of hearing for sound waves in air, two types of measurement have predominated: (1) the minimum audible sound pressure at the eardrum, and (2) the minimum audible sound field in which the observer is placed for listening.

MINIMUM AUDIBLE PRESSURES

A direct measurement of that very small intensity of the sound wave at the eardrum which will just elicit a sensation of hearing is practically impossible. The pressure at the threshold is so small that there has been devised no method sufficiently sensitive to permit its direct measurement at the eardrum. Most methods, therefore, have to establish a known pressure at some measurable intensity, well above threshold, and then determine the amount by which the pressure must be reduced in order to reach the threshold value. Two principal types of procedure

have been used for the determination of the sound pressures at the eardrum

1 A telephone receiver, a thermophone, or an electrody-
namically driven piston is employed as the source of sound and
is held tightly to the ear in such a way as to enclose a known
volume of air. The receiver is calibrated, that is to say, the
sound-energy emitted by the receiver into a closed chamber of
known volume is determined either by the direct optical mea-
surement of the motion of the diaphragm or by the measurement
of the electrical power consumed in the receiver, or else it is
computed from the response of a calibrated microphone placed
in the chamber. Then, knowing the output of the source of
sound and the volume enclosed between it and the eardrum,
one can compute the pressure on the drum. This procedure
requires that certain assumptions be made. It is necessary to
assume that the pressure throughout the ear-enclosure is uni-

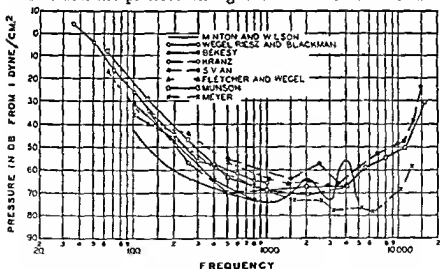


FIG. 14 The minimum audible pressure at the eardrum as determined by various experimenters (After Sivan and White)

form, and it is usually desirable to assume also that the walls of the ear-canal are rigid, although some experimenters have made allowance for the yielding of the drum itself

Several experimenters have employed a procedure in which a receiver is fitted tightly to the ear. The curves in Fig. 14

which were determined in this manner are those of Minton and Wilson, Wegel, Riesz, and Blackman, Békésy, Kranz, and Fletcher and Wegel. The curve for Meyer is the average of data obtained with a telephone receiver and with the ear in an open sound field. Consequently, although Meyer reported no systematic difference between the two methods, it is difficult to say whether or not his results should be grouped with those obtained solely by the method of the tightly fitting receiver.

2. The second method for determining minimum audible pressures employs a small 'search tube' connected at one end to a calibrated microphone. The other end is inserted into the ear so that it is fairly close to the eardrum. Then, if the search apparatus is calibrated, the pressure at the end of the tube near the drum can be determined, and, on the assumption that the pressure at the drum is the same as at the end of the tube, the minimum audible pressure on the eardrum can be measured. Here again it is necessary to measure the pressure at some value well above threshold and then to determine by how much the sound must be attenuated to reach threshold. The data represented in Fig. 14 by the curves for Sivian and for Munson were determined by this method.

THRESHOLD AT LOW FREQUENCIES

Measurement of the absolute sensitivity of the ear at frequencies below 50 cycles is dependent upon an ability to generate extremely pure tones. The characteristics of the thermophone are such that activation by two sinusoidal currents produces a sinusoidal tone whose frequency is the difference between the frequencies of the two currents. Hence, low tones of large amplitude can be produced by allowing pure alternating currents to beat in a thermophone (Békésy, 24). Using this device as a source of sound, Békésy (22) was able to report the measurement of auditory thresholds (minimum audible pressures) at extremely low frequencies. His results disclose, furthermore, that at frequencies below 50 cycles the basic quantal nature of the auditory process manifests itself in a step like threshold curve. By raising the frequency of a tone slowly

and continuously from about 2 to about 50 cycles, one can observe that the loudness and the pitch of the tone do not change evenly, but by jumps. Figure 15 shows a threshold curve obtained by the following procedure. Beginning with about 2

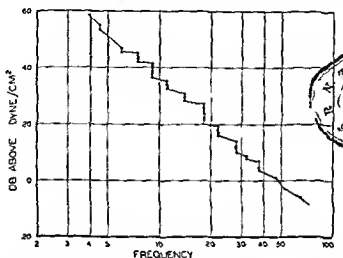


FIG 15 The minimum audible pressures for low frequencies. This threshold curve shows the step-like character which may indicate the quantal nature of the processes involved. The most prominent step occurs at 18 cycles (After Bekesy 22)

cycles at a high intensity, the experimenter decreased the intensity until nothing was heard and then increased the frequency until the sensation reappeared. Thereupon the intensity was decreased (step wise) until the tone ceased to be heard, and again the frequency was raised continuously until the sensation was reported. Below 4 and above 50 cycles no steps could be detected, but between these frequencies steps occurred with regularity at the frequencies shown in Fig 15 (4.5, 6, 7.5, 9, 11, 14, 18, 22, 28, 32, and 38 cycles). Note that the curve in Fig 15 agrees well with what would be a reasonable extrapolation of the curves of Fig 14 (cf Fig 19).

The threshold step at 18 cycles is the most readily detectable. Approaching it from a lower frequency, the observer experiences at 18 cycles a sudden increase in loudness and in pitch. In fact, it is at 18 cycles, according to Bekésy, that we pass

suddenly from the perception of a succession of discrete impulses to a single fused sensation which possesses a truly tonal character. Hence, 18 cycles may be called the fusion frequency of pitch perception (cf Brecher). A decided roughness is present at this frequency, which disappears only gradually with increasing frequency.

What then, we may ask, is the nature of the sensation at frequencies below the fusion frequency? In this region, the observer listening monaurally has the impression that the alternating pressure gives rise directly to a tactual sensation. That this is not tactual in the ordinary sense, Bekesy demonstrates by showing that, under equal binaural stimulation, a tone of 10 cycles gives rise to an auditory sensation which is localized in the middle of the head, and which can be shifted from side to side by altering the intensity of the sound in one ear (see Chapter 6). This cannot be done when tactual pressures are applied to the external ear. Nevertheless, tones of very low frequency do elicit tactual sensations at high intensities (cf Fig 19).

Wever and Bray (9) produced tones with a pistonphone, and investigated the phenomenal correlates of low frequencies. Their observers described four phenomena, noise, intermittence, thrusting effect, and tone, as appearing successively when the frequency was increased from 5 to 60 cycles. A suggestion of tone first appeared at about 20 cycles, although it was accompanied by a noisy flutter. At 25 cycles the tonal component was definite for most observers.

In all this work on tonal thresholds at low frequencies it has not yet been possible to evaluate the role of the aural harmonics (see Chapter 7) in the production of the sensation of tone. At the high intensities needed to stimulate the ear at frequencies below 50 cycles, there are undoubtedly harmonics of great intensity introduced by the nonlinearity and asymmetry of the ear itself. The problem can therefore be phrased: Does the sensation of tone arise when one of the harmonics reaches a certain value of frequency, or must the fundamental itself achieve a certain rate?

MINIMUM AUDIBLE FIELDS

The intensity of a sound wave in free space which will just elicit a sensation of hearing in an observer who enters the space is known as the *minimum audible field*. To determine it, the intensity of the sound is first measured without the observer in the field, and then the observer enters the field and listens to the sound. As for other threshold measurements, the intensity must be determined at a value above threshold and then reduced until the threshold is reached. The intensity at the ear of the observer is obviously not the same as the intensity of the field at that point before the listener entered the field, because an object as large as the human head distorts the sound stream. Nor is the intensity at the ear the same when the head is oriented differently with respect to the source of sound, i.e., when the source is at different azimuths. The effect of the observer's head in the sound field is analogous to that of a ball held in a stream of water—the pressure on the ball is not the same at every point. Furthermore, the variation of sound pressure at the ear with orientation of the head depends upon the frequency of the tone (see p. 168).

In order to avoid inconstancies due to different orientations of the observer, it is advisable to adopt a standard procedure for presenting and listening to tones in free space. It has been proposed (Fletcher and Munson, 1) that the standard manner of listening shall require the observer to face a source, which shall be small, and to listen with both ears at a position such that the distance from the source to a line joining the two ears is 1 meter. Actually, the sound wave at 1 meter from a small source is a spherical wave, but the difference between the effect of such a spherical wave and a plane wave on an object the size of the head is negligible for the present purpose. Therefore, the data obtained under the standard manner of listening can be accepted as valid for plane progressive sound waves in air.

Sivian and White determined the minimum audible field under the standard method of listening for thirteen observers, over the range from 60 to 15,000 cycles. In order to obtain a progressive wave in a closed room it is, of course, necessary to

prevent reflected waves from reaching the observer. Only the wave directly from the source may reach his ears. Thus, Sivian and White placed their source, a loud-speaking receiver, in a highly absorbing acoustic structure called a "sound stage," and seated the observer 1 meter in front of the source. The intensity of the sound field prior to placing the observer in it had been measured (by means of a condenser transmitter whose field calibration was obtained with a Rayleigh disk). The observer was provided with a push button which lighted a small lamp, and he was instructed to press the button whenever and as long as he heard the tone. The experimenter then proceeded to attenuate the tone until threshold was reached. Some of the results of this experiment are shown in Fig 16, together with results obtained by other experimenters.

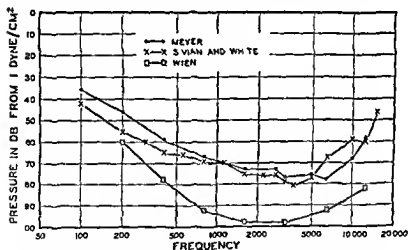


FIG 16 The minimum audible fields as determined by various experimenters (After Sivian and White)

The other curves in Fig 16 represent data of the same type (minimum audible field), but they were not obtained by listening in the standard manner and must be appraised accordingly. The lowest curve is for data obtained by Wien. These thresholds are apparently lower than those obtained by later workers, but the reason probably lies in the manner of presentation of the

stimuli. The observer's head was situated behind a sheet-iron screen and his ear protruded through a hole in the screen. The source was then placed 30 cm from the hole in the screen, so that the sound came to the observer directly from the side rather than from the front. Sivian and White report that one of their best observers, when listening to tones coming from the side (90° azimuth), gave thresholds which agreed closely with Wien's. It appears, therefore, that Wien's data present the thresholds which might be obtained with an observer of very good hearing, listening under the most favorable azimuth conditions.

The data obtained by Meyer are the same, as those recorded in Fig. 14. Plainly, at high frequencies his values resemble measurements by the minimum audible field more closely than by the minimum audible pressures, even though he reported no difference between the two types of measurement.

Many other experimenters (reviewed by Sivian and White) have made measurements of minimum audible fields, although not under the standard conditions of listening. In general their results show less agreement than those obtained for minimum audible pressures (Fig. 14). Some of the important differences between the various sets of data for minimum audible fields are: (1) age of observers, (2) other individual differences, (3) number of ears tested, (4) the type of sound field, (5) the orientation of the observer with respect to the sound field. The last two factors are probably the most important. They account, most likely, for the fact that the variability is greater among field than among pressure measurements.

Even under the most favorable conditions the measurement of thresholds for hearing is beset by factors causing variability, so that the threshold necessarily emerges as a statistical concept. The inherent variability of the observer himself can be easily demonstrated by presenting him with a steady tone at an intensity very near threshold and requiring him to press a button during all the time that he hears the tone. Almost without exception observers press the button intermittently. The threshold should be the most probable value of the stimulus which

will just excite a sensation of hearing, and for that reason it is always necessary to take the average of a series of values which, at different times, have proved just sufficient to elicit a response from the observer. The classical methods of psychophysics (Guilford) have been developed as an aid in determining that value of the stimulus which it is best to call the threshold. Several variations of these methods have been adopted by the experimenters whose work has been discussed.

NATURE OF PRESSURE AND FIELD MEASUREMENTS

In order to determine the most representative set of values for the threshold of hearing in terms of both minimum audible pressure and minimum audible field, Sivian and White re-

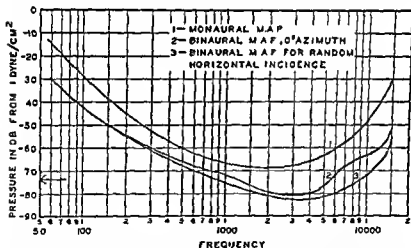


FIG 17 Threshold curves determined for minimum audible pressure (MAP) and minimum audible field (MAF). In drawing these curves Sivian and White gave careful consideration to the results of their own and other experimenters' data. The arrow indicates the standard reference pressure. (After Sivian and White)

viewed most of the previous work done on the subject, and, by considering the nature of each experiment, they were able to arrive at the values represented by the curves in Fig 17. Curve 1 represents the values for the threshold of hearing when measure-

ment is in terms of sound pressure at the eardrum. The curve is a weighted average of the results obtained by several experimenters. In weighting the various results, the number of ears investigated and the experimental procedure employed were carefully considered. The ages of some of the observers, however, were not known, so that we cannot be perfectly sure that curve 1 represents the hearing of young people with no abnormalities. Nevertheless, considering the number of separate studies on which curve 1 is based, and the good agreement among them, the composite curve for minimum audible pressures is probably reliable and valid.

Curve 2 represents the threshold intensity of a sound field when the observer faces the source and listens with both ears. This curve is based almost wholly on the results obtained by Sivian and White, and these results apply definitely to young people with good hearing. In adopting the particular form of the curve shown in Fig. 17, some account was taken of the several other determinations available. The peculiar wavy appearance of curve 2 is due to diffraction of the sound wave around the head of the observer as he faces the source of sound. The pattern of diffraction is not the same at all frequencies. Moreover, the form of curve 2 would be different if some other azimuth had been chosen, such as placing the source at the side instead of in front of the observer.

It is interesting to inquire, therefore, what the form of the threshold curve would be if the source were moved continuously around the head of an observer with equally good hearing in both ears. What would be the threshold curve for the case in which the sound is able to reach the observer directly from all sides? Knowing the curve for the case in which the observer faces the source, and having at hand adequate data on the form of the 'sound shadow' cast by the head at different frequencies, we can calculate the minimum audible field for random incidence of the sound. The result of such a calculation is depicted by curve 3 in Fig. 17. At all except the low frequencies, where sound shadows are very slight, the thresholds for random incidence are lower than those obtained with the

observer facing the source. This result is to be expected, because, with the sound coming from all directions, the minimum depends on the optimum direction for the orientation of the head relative to the source of sound at every frequency.

In Fig 17, curve 1 is for monaural listening. Curve 2 is indicated as representing binaural listening. Before comparing the two sets of data it is well to inquire as to the effect of binaural listening on the auditory threshold. In the data of Sivian and White, the monaural thresholds were hardly distinguishable from the binaural thresholds. That is to say, the rather large variability of threshold data prevented any reliable difference from being established between monaural and binaural thresholds. Other experimenters, however, have shown that the threshold for binaural listening is lower than for monaural. In fact, Hughes has demonstrated that, in order to reach threshold, the total energy required when the tone is led to the two ears is equal to the energy required in one ear, regardless of the actual division of energy between the two ears. Any fraction of the energy needed to produce a sensation of hearing in one ear can be diverted to the opposite ear and a sensation still results. Thus a subliminal stimulus in the right ear lowers the threshold for the left, and this occurs even when the tones in the two ears are of different frequency. Holway and Upton likewise showed that throughout the audible range of frequencies the binaural threshold is lower than the monaural threshold for either ear. Each of thirty subjects tested with a tone of 800 cycles showed this effect, and for a majority of these persons the difference between the binaural and monaural thresholds was approximately 6 db. Hence it appears that the nervous excitations from the two ears summate when the stimuli are *in or below threshold*, just as they do for louder tones (see p. 115), and consequently the threshold for listening with both ears in an open sound field should be lower than that obtained with a receiver on one ear. This fact may account for some but not all the difference between curves 1 and 2 in Fig 17. Let us consider, therefore, some additional items affecting the measurement of thresholds.

COMPARISON OF PRESSURE AND
FIELD MEASUREMENTS

The values for minimum audible fields lie from 10 to 20 db below the values for minimum audible pressures when the latter are measured at the eardrum. In other words, we are faced with the apparent contradiction that, when an observer is listening to a tone which he is just able to hear, the intensity of the sound field outside his ear is less than the intensity at his eardrum. The resolution of this difficulty must, of course, lie in the discovery of factors which tend to prejudice the measurement of sound intensities in one or the other, or both, of the two cases. As yet, however, we can only suggest what some of these factors might be, we cannot prove that they account for all the discrepancy. At high frequencies we might well expect the two types of measurement to differ because of sound shadows (diffraction) caused by the head and the pinnae, and because of anomalous wave motion in the auditory canal, even though the physical measurements were perfect in both cases. For frequencies in the middle range, it can be shown that the sound pressure at the eardrum is greater than that in the external sound field, because of the resonance of the external ear-canal. The resonant frequency of this small chamber is very near 3000 cycles, and consequently, near this frequency, the pressure at the drum may be as much as 3 times greater than the pressure outside the meatus (Békésy, 11). At low frequencies, however, where measurements of pressure at the eardrum are most reliable, where resonance effects are *nil* where diffraction is slight, and where, also, the age of the observer is of less moment, it is difficult to account for the wide differences between curves 1 and 2 in Fig. 17.

It is conceivable that the effect called *physiological noise*, which is associated with the tight fit of the sound receiver on the ear, may mask the tones (see Chapter 8) when minimum audible pressures are being measured. On account of pulse actions, breathing, etc., mechanical vibrations are set up in the enclosed space whenever a receiver is pressed to the ear (Békésy, 24). This is the same effect that delights children when they

hold a sea shell to their ear and listen to the "ocean's roar" The sensation is of a low frequency noise which tends to raise the thresholds, particularly for low frequencies

Other factors, whose effects are difficult to evaluate, are the changes in static pressure and the temperature in the ear-canal when a receiver is on the ear These factors might affect the acoustic impedance of the eardrum and also cause fatigue and annoyance A tightly fitting receiver might also introduce variable amounts of interference from bone conduction (see p 291)

Another factor which might play an important part in differentiating open field hearing from hearing with the receiver fitted tightly to the ear is the change in tension of the muscles of the middle ear for sounds of different intensity Loud sounds cause the tensor tympani to contract and exert a tension on the eardrum, which in turn impedes the transmission of acoustic vibrations from the external to the inner ear (see p 266) Now, pressure measurements are necessarily made at an intensity well above threshold—about 60 db—and the sound is then attenuated until threshold is reached Field measurements, on the other hand, can be made at levels much nearer threshold It may be that in the case of pressure measurements, as the sound is attenuated the tension on the drum is relaxed, so that the acoustic impedance of the ear is changed, especially at low frequencies This change of impedance would mean that the energy consumed in driving the eardrum is not a linear function of the energy emitted by the receiver, and consequently the true threshold of hearing cannot be measured in terms of the amount of attenuation at the receiver

A final evaluation of these several factors which influence the measurement of minimum audible fields and minimum audible pressures is not possible at present

RELATION OF THE AUDITORY THRESHOLD TO THE REFERENCE INTENSITY

It is interesting to compare the auditory thresholds to the standard threshold (reference intensity), in terms of which it

is customary to express acoustic intensities (see Glossary) The reference intensity is, for a plane progressive sound wave, equivalent to a pressure of 73.8 db below 1 dyne per square centimeter This value is indicated by the arrow on the ordinate scale of Fig 17 The minimum audible pressure in the region where the ear is most sensitive (2000 to 3000 cycles) is about 5 db above the reference intensity On the other hand, the minimum audible field is almost 10 db below the standard level of reference in the same region

THE AMPLITUDE OF MOVEMENT OF THE EARDRUM AT THRESHOLD

The absolute displacement of the eardrum at the threshold of audibility is extremely small—much too small to be measured directly, for, throughout the region where the ear is most sensitive, the drum moves through a distance equal only to about one thousandth of the wave length of light Hence, the measurement of amplitude must be made at a frequency or intensity at which displacement is measurable, and then the amplitude at threshold may be determined by extrapolation

A recent method (Wilska) made use of a device, similar to an electrodynamic loud speaker, to drive a light wooden shaft, 8 cm long, one of whose ends was cemented to the eardrum The other end was fastened to the moving coil of the electromechanical transducer which was mounted rigidly on the side of the subject's head Then, with a microscope, the amplitude of motion of the shaft was determined as a function of the frequency and magnitude of the current in the moving coil This could be done only at low frequencies However, it was assumed that (1) the amplitude decreases inversely as the square of the frequency and (2) directly as the magnitude of the current in the moving coil Then, by measuring the current at the threshold of hearing for different frequencies, the experimenter could calculate the absolute movement of the eardrum at threshold The results are shown by the circles in Fig 18

For purposes of comparison, the solid curve in Fig 18 gives the amplitude of motion of the air particles in a plane sound

wave whose root-mean-square pressure equals the threshold pressure shown in Fig 17. The agreement between the two types of measurement is satisfactory and confirms the fact that the ear is sensitive to extremely minute movements. Even slightly less movement may occur at the oval window and

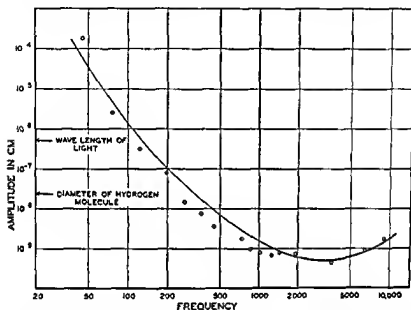


FIG 18 The circles show the amplitude of vibration of the eardrum at threshold, as determined by Wilska. The curve represents the calculated amplitude of the air molecules in a sound wave at threshold pressure. Where the ear is most sensitive the amplitude of vibration of the eardrum is less than the diameter of a hydrogen molecule.

within the cochlea for threshold stimulation. Consequently, it appears that near 3000 cycles we are able to detect a displacement of the basilar membrane equal to about 10^{-19} cm. This distance is less than 1 per cent of the diameter of a hydrogen molecule!

THEORETICAL LIMITS OF AUDITORY SENSITIVITY

In view of the very small amount of acoustic energy needed to excite a sensation of hearing in a good ear, the question arises

as to whether the sensitivity of the ear is limited by its construction and its physiological efficiency or whether the limit is imposed by the nature of the air as a transmitting medium for sound. We know, from experiments on Brownian movement, that the individual molecules of the air are constantly in random agitation with a violence dependent upon the temperature of the air. On any surface exposed to the air, therefore, there are tiny periodic fluctuations in pressure, caused by the irregular distribution of thermal velocities among the air molecules. The result is a spectrum of thermal acoustic noise in which all frequencies are represented. The question then is: Are the frequencies to which the ear is most sensitive present in the thermal noise at an intensity great enough to be heard?

An approximation to the solution of this problem was worked out by Sivian and White along lines analogous to the method used in determining the electromotive force produced by the thermal agitation of electric charges in conductors. The random motion of the charges on the atoms composing an electric conductor and the random motion of air molecules produce analogous effects. By limiting the consideration to pressures generated within a limited band of frequencies, it is possible to calculate these pressures. Thus, calculation shows that between the frequencies 1000 and 6000 cycles the root mean square pressure due to thermal agitation is about 86 db below 1 dyne per square centimeter. Throughout that region the minimum audible field averages about 76 db, but in cases of persons with particularly excellent hearing it may average about 85 db below 1 dyne per square centimeter. The calculations of the pressure due to the thermal noise in air are admittedly crude, but they serve, nevertheless, to demonstrate that, in the region of maximal sensitivity, the minimum audible field for a good ear has a pressure of the same order of magnitude as the thermal acoustic pressure at ordinary temperatures. For exceptionally acute ears, therefore, a further increase in sensitivity would be useless in the face of the normal noise continuously present in the air. This fact makes it highly unlikely that there should be animals having appreciably greater auditory sensitivity than man in the

region between 1000 and 6000 cycles, for they too would be limited by thermal noise

A problem analogous to that of thermal noise has been raised in regard to differential visual acuity. Barnes and Czerny conclude that there is evidence to show that the human eye, in that region of the visual spectrum to which it is most sensitive, has a differential sensitivity of the same order of magnitude as the fluctuations inherent in a 'steady' light due to the shot effect' in photon emission. Nature has apparently produced sensory receptors in man, whose effectiveness is limited only by the quantal nature of the phenomena they are designed to discriminate

THE THRESHOLD OF FEELING

As the intensity of an audible sound is increased, a point is reached at which the listener experiences a nonauditory tactual sensation. This is usually described as 'feeling,' but its nature varies considerably with frequency and somewhat with observers. At lower frequencies a gentle but definite vibration is experienced which is quite distinct and superimposed on the sound. In some cases, however, "dizziness" is described, suggesting excitation of the semicircular canals. At higher frequencies the sensation is likely to be one of sharp pain.

A determination of this threshold of feeling, by allowing the observer to increase the intensity until the extra auditory sensation appeared, gave the results shown by the circles in Fig 19 (Wegel, 2). This threshold corresponds closely to the loudness level of 120 db (see p 124), and may be taken as defining the upper limit of hearing. The area then, between the threshold of feeling and the threshold of hearing, shown by the lower curve in Fig 19, is known as the *auditory area*. It delineates the audible range of frequencies and intensities when measured in terms of sound pressure at the eardrum.

The section of the threshold curve for hearing lying below 50 cycles is due to Békésy (22), who reports auditory phenomena at astonishingly low frequencies. In addition to the purely auditory sensations, which exhibit the usual phenomena of

localization (see p. 46), Békésy describes three other types of sensation, whose thresholds are plotted in Fig. 19. When, at 10 cycles, the intensity in the two ears is increased about 40 db above the threshold of hearing, one experiences a tactual sensation which is definitely localized at the ears and cannot be

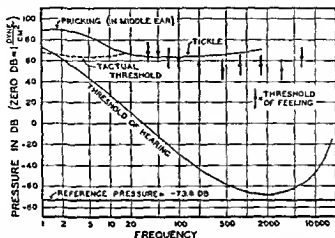


FIG 19 The auditory area, which lies between the threshold of hearing and the threshold of feeling. The threshold of hearing represents minimum audible pressure. Wegel (2) determined the values for the threshold of feeling. The vertical lines represent the scatter of his observations. The other curves were determined by Békésy (22).

shifted by unequal intensities in the two ears. This threshold is represented by the dotted curve in Fig. 19. At frequencies below 1 cycle, the tactual sensation appears before the auditory. For extremely slow frequencies, such as 1 cycle in 30 sec, the tactual threshold is reached at about the same value of pressure. Furthermore, this tactual sensation, although it resembles phenomenally a sensation of pressure on the tip of the finger, shows extremely slow adaptation and persists for several minutes when a constant pressure of about 6000 dynes per square centimeter is applied.

Stimulation at still higher intensities, at frequencies below 10 cycles, arouses a definite pricking sensation which synchronizes with the maximum of the pressure-wave and which appears to be localized much deeper in the ear than the tactual sensation. At frequencies above 20 cycles, the pricking passes

over into a sensation of tickle and completely masks the tactual sensation. Undoubtedly, this sensation of tickle corresponds to what was reported by Wegel (2) as "feeling." It shows very little dependence upon frequency or wave form, but arises at any frequency when a sufficient amplitude is reached. Further increase in intensity changes the sensation from a tickle to an itch, and the itching may persist for several minutes after the tone has ceased. The persistence of the tickle, however, is only about 0.02 sec. Finally, Békésy reports that long-continued stimulation at intensities above the threshold for tickle produces a painful burning sensation which resembles the burning produced when the skin is rubbed severely. When this burning occurs, the experiment must be discontinued!

AUDIOMETRY

A reliable method for making accurate measurements of the threshold of hearing for tones of various frequencies is of great value to otologists, clinicians, school teachers, and many other persons. Consequently, the more picturesque rule-of-thumb methods for testing hearing, such as whispering to the patient or holding a watch at various distances from his ear, have given way to the audiometer. The commercial audiometer is designed to determine the acuity, and, to some extent, the quality of hearing. It consists of a vacuum tube oscillator equipped to produce tones of several fixed frequencies at definitely measurable intensities. These tones are generated at the ear of the listener by a receiver which has previously been calibrated in terms of the hearing of a 'normal' ear. Then, by measuring the amount by which the intensity of a given tone must be increased above the 'normal' intensity in order for the patient to hear the tone, the investigator obtains a measure of the impairment of hearing for that tone. The test tones usually have frequencies spaced an octave apart throughout the audible range, and the 'normal' intensity at each frequency is determined from measurements on a large group of young people. The standard procedure for testing hearing requires that the patient hold the receiver snugly to his ear and press a signaling

button during all the time he hears a tone. The button lights a lamp. Then, at each frequency in turn, the intensity is adjusted until it reaches the lowest value for which the patient is able consistently to signal that he hears the tone. This value of the intensity is taken as the threshold, and the relation of this value to the 'normal' intensity determines the patient's relative acuity. In order to facilitate the determination of this relation, the dial by which the intensity is controlled is calibrated directly in decibels (sometimes called "sensation units"), so that the operator obtains a direct reading of the number of decibels that the patient's threshold is above or below normal.

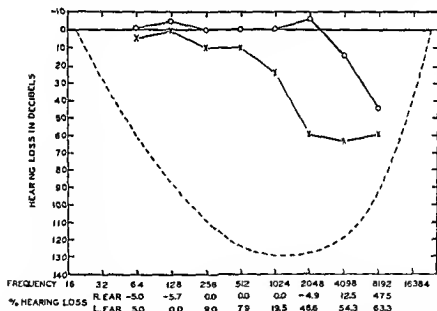


FIG 20 An audiogram for a person suffering from high tone deafness. The circles are for the right ear, the crosses for the left. The dotted curve represents a hearing loss equal to 100 per cent at all frequencies. The useful auditory area is enclosed between this curve and the zero ordinate. The zero ordinate represents normal hearing.

THE AUDIOGRAM

Results of audiometric measurements are usually plotted on what is called an *audiogram*. A sample audiogram, obtained with a commercial audiometer, is shown in Fig. 20. The ab-

scissa represents the frequency of the tones presented, and the ordinate measures, in decibels, the amount by which hearing is below normal. The dotted curve represents, approximately, what is known as the *threshold of feeling*. When a tone is made sufficiently intense, the observer experiences a tactual (feeling) sensation, and the distance on the audiogram from the line representing normal hearing to the dotted curve is a measure of the intensity above threshold at which feeling occurs. The area between the normal line and the dotted curve is commonly referred to as the *auditory area*. Another way of plotting the auditory area is shown in Fig. 19.

Clearly, if a person is unable to hear a particular tone, even when the intensity is made so great that his threshold of feeling is reached, his *hearing loss* at that frequency, for all practical purposes, is 100 per cent. On the other hand, if he hears the tone when its intensity is raised to a value midway between the normal threshold and the threshold of feeling his hearing loss is only partial. This procedure for determining hearing loss suggests a method for designating the state of a patient's hearing. Thus if for a tone on the audiogram in Fig. 20, the intensity which the listener is just able to hear lies halfway between the normal threshold and the threshold of feeling we say the hearing loss at that frequency is 50 per cent. In other words, one hundred times the ratio of the distance of the threshold point from the normal line to the distance of the normal line to the threshold of feeling is taken as the percentage of hearing loss at that frequency. The figures at the bottom of Fig. 20 give the percentage of loss for the two ears whose audiograms are plotted.

It must be borne in mind that this manner of designating hearing loss is based upon an arbitrary procedure, and, although the method is convenient and standard care is needed in its interpretation. The ordinate of the audiogram is a *logarithmic scale* since it is measured in decibels. Hence, to say that a person has a 50-per-cent hearing loss does not mean that the *energy* of the stimulus must be raised to 50 per cent of its value at the threshold of feeling in order for him to hear

the tone. (Actually, the threshold energy for hearing, of a person with a 50-per-cent hearing-loss, is equal to the square root of the energy at the threshold of feeling.)

It is commonly supposed that the logarithmic scale of sensation units (decibels) is a true measure of the subjective loudness of a tone, and that the measurement of hearing loss in sensation units is essentially a valid subjective measure. Loudness, however, is not proportional to the logarithm of the stimulus—the Weber-Fechner law does not hold here (see Chapter 4). Consequently, a hearing-loss of 50 per cent does not mean that the loudness of a tone, as judged by a normal observer, must be increased to 50 per cent of its loudness at the threshold of feeling in order to be heard by the patient. In fact, recent determinations of values of subjective loudness demonstrate that a tone of 1000 cycles which, on the audiogram in Fig 20, is halfway between the normal line and the threshold of feeling has a loudness, for a normal listener, which is only about 1 per cent of the loudness of the same tone at the threshold of feeling.

Clearly, then, the percentage scale used for measuring hearing loss agrees neither with the physical measure of the intensity of the stimulus nor with the subjective measure of the loudness of a tone. It is, however, a convenient scale, since it has all of the advantages of the decibel scale (discussed in Chapter 1), and its widespread use by those interested in clinical studies warrants its retention.

TONAL LACUNAE

Tonal lacunae are commonly understood to be isolated regions of frequencies to which the ear is not sensitive. The sensitive regions between tonal lacunae are called *tonal islands*. In most cases of supposed insensitivity to certain frequencies, it is found that, by increasing the intensity of the stimulating tone, a value is found which results in a sensation of hearing. In other words, tonal lacunae turn out to be regions of relative rather than absolute insensitivity. The audiogram for the left ear in Fig 20 illustrates this point. At 4096 cycles the hearing-loss, in decibels, in the left ear is greater than at fre-

quencies an octave removed on either side. If this ear were being tested with a tone 60 db above threshold, a range of inaudible frequencies would be found near 4096 cycles. This tonal lacuna would disappear, however, as soon as the intensity was increased to 70 db above threshold.

SENSITIVITY BY BONE CONDUCTION

The determination of normal thresholds for hearing by bone-conduction is of great practical importance to the otologist. Unfortunately, the nature of the process—the application of a small vibrating diaphragm to the mastoid bone behind the pinna—precludes the specification of bone-conduction thresholds in simple energy units, such as are used in hearing by air conduction. The amount of energy delivered to the ear by bone-conduction is difficult to determine. It is, of course, possible to measure the power delivered to the bone-conduction receiver, but how much of this power is passed on to the auditory mechanism depends upon the type of receiver used, and the manner of its application to the head of the subject. For testing a person with normal hearing, the external ear-canal must be stopped off, but the question remains as to how much sound energy reaches the eardrum of the listener by what is essentially air-conduction, i.e., transmission through the stopped meatus.

If we assume that the sound heard at threshold reaches the ear exclusively by bone-conduction, we can then proceed on an empirical basis to the construction and calibration of a bone-conduction audiometer. As with the audiometer for determining sensitivity to tones by air-conduction, the instrument can be calibrated in terms of the hearing of a large number of normal observers, and hearing loss in abnormal ears can then be measured in terms of the amount by which the power delivered to the bone-conduction receiver must be augmented in order to excite a sensation of hearing. The bone-conduction audiometer is, in the hands of the otologist, an important diagnostic aid for determining causes of deafness (see Chapter 11).

SENSITIVITY TO ELECTRICAL STIMULATION

The auditory sensitivities discussed thus far have pertained to some form of mechanical stimulation. It is possible, however, to elicit a sensation of hearing by delivering electrical rather than mechanical energy to the ear. In other words, when an alternating electric current is passed through the head of an observer, he hears, under proper conditions, a tone whose pitch depends upon the frequency of the current. This phenomenon has been called the *electrophonic effect* (Stevens, 8).

Electrophonic thresholds have been determined by measuring the minimal power needed, at various frequencies, to arouse an auditory sensation, with electrodes applied in a standardized manner. One electrode consisted of a metal plate in contact with the inside of the observer's forearm. In order to make contact with the other electrode at the ear, the external meatus was filled with a salt solution and a bare wire was immersed about 5 mm in the solution. The two electrodes were then connected to a beat frequency oscillator, through an ammeter and vacuum tube voltmeter, so that the voltage and current delivered to the observer could be measured simultaneously.

As is well known, the body presents to an alternating current a complex impedance which has resistive and capacitive components. Therefore, in order to measure the power dissipated, the equivalent resistance and reactance of the portion of the body in the path of the alternating current must be determined. This can be done by connecting the two electrodes to an impedance bridge, and measuring the resistance and the reactance of the observer. The resistance and the capacitive reactance decrease with increasing frequency. From the values obtained from the impedance bridge it is possible to calculate the *power factor* of the observer—the ratio of the resistance to the total impedance—at each frequency, and then to calculate the actual power consumed when a threshold current is passed through the body.

The results of a series of threshold measurements, on observers whose hearing by air-conduction was tested by means of an audiometer and found to be normal, are shown in Fig. 21.

(Stevens, 8). The lower curve represents the power needed to reach the threshold of hearing; the upper curve shows the point at which an electric shock is felt. The fact that an increase above threshold of about 20 db in the intensity of the stimulus gives rise to a combined burning, tickling, and prickling sensation severely limits the loudness which may be achieved through electrical stimulation. The 'auditory area' under electrical

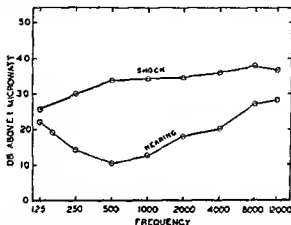


FIG 21 The power required to produce a sensation of hearing when an alternating current is passed through the head. A sensation of electric shock is experienced at values given by the upper curve. The usable auditory area' under electrical stimulation is the area between these curves (Stevens, 8)

stimulation is much smaller than under conditions of normal stimulation by sound-waves in air. The electric shock also imposes limits to the range of frequencies which can be detected, for, when the frequency of a pure tone is as low as 200 cycles, most observers experience shock before they hear the tone. Similarly, at frequencies above 10,000 cycles, the threshold for shock is usually less than for hearing. Nevertheless, as shown in Fig 21, observers sometimes hear tones as low as 125 cycles and as high as 12,000 cycles. In hearing a tone as low as 125 cycles, there appears a combined auditory, tactual, and pressure sensation in the ear, which observers report as a "strange experience."

If the wave-form of the low tone is extremely nonsinusoidal,

the threshold frequency may be considerably lowered. In fact, when the wave form approximates that of a series of sharp impulses, the observers hear a corresponding series of clicks at the frequency of the impulses, regardless of how low that frequency may be. This fact probably explains the report of some experimenters (Gersuni and Volokhov) that thresholds have been measured for tones as low as 17 cycles. The tones were apparently not produced by sinusoidal waves.

In the measurement of thresholds for electrical stimulation, we face the same problem as for bone conduction, that is, we cannot determine precisely how much energy is delivered to the auditory mechanism itself. The ideal measure of the electrophonic thresholds would be the amount of power dissipated in the particular mechanism by which electrical energy is transformed into acoustical energy, but, since there is, at present, no way of discovering how much of the total energy dissipated between the two electrodes is consumed in hearing, the best measure appears to be the total power used when the electrodes are applied in some standardized manner. Probably only a small fraction of this total power is consumed in the auditory mechanism—only enough, in fact, to set up minute mechanical vibrations in the basilar membrane (see p. 352).

RELATION OF SENSITIVITY TO AGE

Like most other organs of the body, our ears grow old and lose some of their effectiveness. The auditory mechanism is peculiar, however, in that it tends to lose its sensitivity to certain frequencies, but not to others. Thus, we find that older people grow increasingly less sensitive to tones of high frequency—above 1000 cycles—but retain their hearing for low tones excellently.

An extensive series of audiometer tests on 353 hospital patients was carried out by Bunch. The results are classified for age groups by decades, and, as shown in Fig. 22, the outstanding result is the marked decrease in acuity with advancing age. The label on each curve indicates the lower limit of the decade

The number of patients in the successive decades was 68, 70, 78, 85, and 52.

Another series of tests was conducted by Montgomery (1) on 200 people, ranging in age from 20 to 60 years. These tests also indicate decreasing sensitivity with advancing age, though not so markedly as in Bunch's work. The difference may be

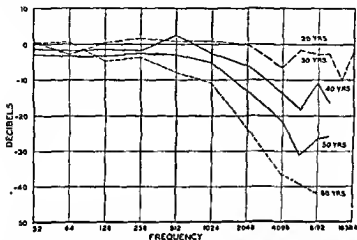


FIG. 22. The audiograms of people at different age-levels. The ordinate records the hearing loss, in decibels, relative to the hearing of people whose ages lie between 20 and 30 years (zero ordinate). (After Bunch.)

attributed to the fact that the hospital group, examined by Bunch, included more people whose ailments accentuate the normal effects of advancing age than would be found in a healthy group, such as Montgomery investigated. Montgomery found that the difference between the 20-29 and the 50-59 decades is about 7 db at 2048 cycles and 23 db at 8192 cycles.

CHAPTER 3

PITCH

PITCH is one of the psychological aspects, or attributes, of tones. It is one of the dimensions in terms of which we are able to distinguish and classify auditory sensations. Thus we commonly describe high frequency tones as *high* pitched tones, and to tones of low frequency we attribute a *low* pitch. This designation of pitches in most European languages by words meaning high or low appears to have some basis in phenomenal experience. When observers are asked to localize the apparent source of tones produced behind a screen, they are likely to attribute a higher locus to the high pitched tones than to the low, even though the actual source of the tones remains unchanged (Pratt, 3).

The scale on which we arrange the pitches in order is generally assumed to have definite lower and upper limits—corresponding approximately to the frequencies of 20 and 20,000 cycles. The lower limit for auditory sensation is not necessarily the lower limit for the perception of pitch. Tonal pitch has been reported to arise quite suddenly at 18 cycles, whereas some sort of hearing may be possible near 1 cycle (see Chapter 2). The lower limit for pitch is difficult to determine with precision, for two reasons. First, there is the problem of distinguishing between a very low frequency which is heard as a tone and one which is heard simply as a series of distinguishable pulsations. Second, the ear itself introduces so much distortion (the production of aural or 'subjective' harmonics) at these low frequencies that the task of distinguishing between the perception of the fundamental tone and the hearing of higher harmonics becomes difficult. For certain low frequencies, the aural harmonics of an originally pure tone may have a higher sensation level than the fundamental itself, and the harmonics may possibly be heard as tones when the fundamental is too faint

to be heard at all (see p 187) The upper limit of hearing, for a given individual, can be determined with greater precision, but in this case the marked differences among persons and the striking effect of age upon the upper limit prevent any attempt to fix a 'normal' upper limit (see p 68)

Pitch is a concept determined by the direct response of a human observer to a sound stimulus. Frequency, on the other hand, is determined by an observer who uses the instruments of physical observation and measurement. That is to say, frequency is measured with the help of instruments, pitch is a direct perception. It is necessary to stress this difference between the two concepts, because of the persistent tendency to confuse pitch with frequency. Physicists have generally used the two words interchangeably, on the false assumption that experienced pitch is uniquely determined by the frequency of the stimulus. Thus Barton, in his excellent treatise on sound says, 'The pitch of a musical sound depends upon the period or frequency of the vibrations constituting the sound and upon that alone

THE RELATION OF PITCH TO INTENSITY

Many investigators, during the last hundred years, have noted an apparent change in the pitch of a tone with a change in intensity (Zurmuhl). An instance of this effect (Miles) appears when observers are required to reproduce vocally the pitch of a tuning fork (middle C). When the fork is held close to the ear so that the intensity is increased, the pitch of the singer's voice is lowered slightly. In other words, the observers hear the louder tone as lower.

In order to determine quantitatively the effect of intensity upon the pitch of tones throughout the audible range, a survey was made of the phenomenon for 11 frequencies ranging from 150 to 12 000 cycles (Stevens 5). Two tones of slightly different frequency were presented alternately to an observer. He was allowed to adjust the intensity of one of the tones until the pitch of the two tones appeared equal. In other words, the observer compensated for a difference in frequency by means

of a difference in intensity, and thereby made the two tones sound equal in respect of pitch.

The results of extensive observations made with one observer

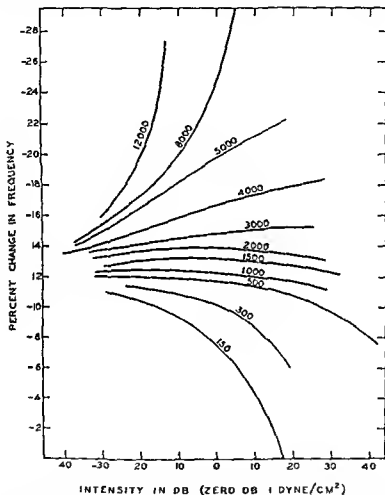


FIG 23 Contours showing how pitch changes with intensity. The percentage change in frequency necessary to keep the pitch of a tone constant in the face of a given change in intensity can be taken as a measure of the effect of intensity upon pitch. Pitch in this case is the parameter, as indicated by the numbers attached to the curves. The ordinate scale was arbitrarily chosen so that a contour with a positive slope shows that pitch increases with intensity (After Stevens 5)

who was exceptionally accurate are shown in Fig 23. These curves we may call *equal-pitch contours*. They show the rela-

tion between frequency and intensity which must be maintained in order to keep a tone at a constant level of pitch. Hence they show what happens to the pitch of tones of various frequencies when we alter the intensity. For low tones, the pitch decreases with intensity, but, for high tones, the pitch increases with intensity. For certain tones in the middle range, both effects are present to a slight degree. Thus at 2000 cycles, the pitch, for this observer, increased up to about 60 db above threshold and then decreased. At other frequencies this point of reversal occurred at different intensities. In general, the higher the frequency, the higher the intensity at which the reversal takes place.

Now, casual inspection of Fig 23 shows that the frequencies at which the change of pitch with intensity is least are those to which the ear is most sensitive, as shown in Fig 17 (p 50). Apparently the point of maximal sensitivity of the ear is the point at which the reversal of the direction of the pitch-change occurs. Then, the tendency of the reversal to take place at higher frequencies when the intensity is raised, as shown by the maxima of the middle group of curves in Fig 23, should mean that the frequency to which the ear is maximally sensitive is a function of intensity. This inference is borne out, in a qualitative manner, by a study of the equal loudness contours shown in Fig 45 (p 124). The minima of those curves represent the points of maximal sensitivity at different loudness-levels. There is clearly a slight shift of the minima in the direction of the higher frequencies as the intensity is increased.

In this phenomenon we have a case of a physical system (the ear) whose frequency-characteristic is a function of the magnitude of the driving force. That is to say, the resonant frequency of the total auditory mechanism, as represented by the minima of the equal loudness contours, is not the same frequency at all intensities. This fact means that, as the intensity is raised, some mechanism comes into action which has a selective effect upon different frequencies. Apparently this mechanism attenuates the response of the ear to low but not to high frequencies, as the intensity is raised. Now, a mechanism which has precisely

this effect is the musculature of the middle ear (see p 266) Tension on the tensor tympani, which occurs reflexly in response to loud sounds, serves to tighten the eardrum and to impede the transmission of low tones This selective attenuation of low frequencies at high loudness levels may well account for the shift in the point of maximal sensitivity of the ear, and presumably makes it reasonable to expect the shift in the maxima of the pitch-contours of Fig 23

The foregoing discussion rests upon the assumption that the forms of the loudness- and pitch-contours depend upon the response-characteristics of the auditory mechanism when it is viewed as a total system We may thus inquire what is the relation of the change of pitch with intensity to the behavior of the mechanism in the inner ear—the basilar membrane In terms of the mechanics of the basilar membrane (Chapter 10), the change of pitch with intensity is represented by a shift in the position of maximal stimulation on the membrane Since high tones become higher and low tones become lower with increased intensity, it is clear that the stimulation moves out toward the ends of the membrane, for high and low tones What happens for tones of the middle range? Here the shift is closely related to the point of maximal sensitivity of the ear, and the shift is always such as to move the region of maximal stimulation on the basilar membrane away from the point which is stimulated by the frequency to which the ear is most sensitive In other words, as the intensity of tones is increased, their pitch is shifted away from the pitch of the tone to which the ear is maximally sensitive

Here we have a phenomenon bearing a striking resemblance to the Bezold Brücke effect in vision, according to which alteration of the intensity of a visual stimulus produces a change of hue The analogy holds even further, however, for just as there are frequencies at which pitch is invariant with intensity, so likewise does hue remain invariant with intensity at certain wave lengths of light

A possible explanation of the change of pitch with intensity is presented on p 349

CHANGE OF PITCH FOR VERY LOW TONES

An investigation of the behavior of the pitch of tones below 300 cycles (Snow) shows that the lower the tone, the greater the change of pitch for all tones above approximately 100 cycles. Below 100 cycles the magnitude of the pitch-change decreases, but the direction of the change remains the same. This generalization must be modified for extremely loud tones, for at high loudness-levels (above 105 db) the greatest change of pitch appears to occur at about 200 cycles.

The comprehensive set of curves shown in Fig 24 were drawn to illustrate the behavior of the pitch of low tones. These

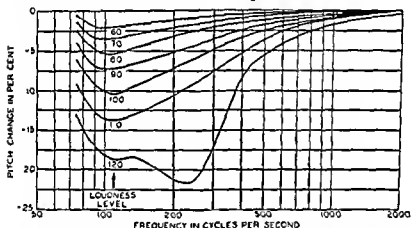


FIG 24 Contours of constant loudness-level. The curves show the amount by which the pitch of a pure tone of any frequency is shifted as the tone is raised from a level of 40 db to the level indicated on the contour. Example: the pitch of a 100-cycle tone is lowered 10 per cent when its loudness level is increased from 40 db to 100 db, but the pitch of a 500-cycle tone is lowered by only 2 per cent by the same change in loudness-level. (Snow)

are probably the most representative curves that can be constructed on the basis of present evidence. Our ability to determine precise functions for the phenomenon of change of pitch is restricted by the fact that large differences appear among the results obtained with different observers. Nor is there great agreement between the results obtained from the same observer on different days. It is an interesting fact, however, that those observers, in two different experiments, who showed the largest

changes of pitch with intensity were the most consistent in their judgments (Stevens, 5, Snow)

On the basis of the hypothesis previously laid down to explain the relation of pitch to intensity, namely, the displacement of the pattern of cochlear excitation toward the end of the basilar membrane, it is reasonable to expect that the magnitude of the change of pitch would decrease at very low frequencies. When the excitation is already close to the end of the membrane, further shift in that direction should be difficult. There is also the possibility that at frequencies below 100 cycles (Steinberg) the perception of pitch does not depend in a simple manner upon a point of maximal stimulation, because the entire apical end of the membrane may be involved for these low tones (see p 375). In this event anomalous behavior of the pitch of low tones is to be expected.

The argument may well be made that we have, in this phenomenon of change of pitch with intensity, a means of finding the frequency below which spatial localization of excitation on the basilar membrane is not the important determinant of pitch. Spatial differentiation (the 'place theory' of pitch) should not hold below the lowest frequency at which intensity has an effect on pitch. Unfortunately, this point has not yet been determined.

CHANGE OF PITCH FOR MUSICAL TONES

It must be emphasized that the pitch changes shown in Figs 23 and 24, which may seem very large, were obtained with pure tones. These changes, of more than a full musical tone in many cases, would undoubtedly have strange effects upon musical renditions if pure tones were used. Fortunately, however, the complex tones produced by most musical instruments suffer only very slight changes of pitch with intensity. Thus when four skilled musicians were asked to play a certain interval on a violin, first very softly and then very loudly, the relation between the objective frequencies constituting the interval was not significantly different in the two cases. Since the players were judging the intervals in terms of subjective pitch, this

result seems to indicate that the pitch was not changed by intensity (Lewis and Cowan)

Additional evidence that the pitch of impure tones is relatively stable was obtained by comparing the change of pitch in a 5 partial tone (fundamental frequency of 200 cycles) with the change in a pure tone of 200 cycles. The change in the pure tone was about 5 times as great (Fletcher, 3). This difference between pure and complex tones apparently depends upon the fact that the complex tone contains, as partials, those frequencies whose pitch, as shown in Fig 23, changes very slightly with intensity. Perhaps these partials control the magnitude of the apparent change of pitch when the complex tone is varied in intensity.

Finally, it is of great musical interest to determine whether the harmonious relation of two tones depends upon the pitch or upon the frequency of the tones. Will two tones constituting an octave when sounded separately be harmonious when sounded together? The answer, of course, depends upon the intensive relations involved. For example, a soft tone of 300 cycles may appear to be an octave higher than a loud tone of 168 cycles, but when they are sounded together they are very discordant. The reverse can also be demonstrated, that is, two tones which appear to be slightly different in pitch may, when sounded together, produce a harmonious result (Fletcher, 4). We must conclude, therefore, that tonal combinations will be harmonious or not, depending upon the *frequencies* rather than upon the *pitches* of the components.

RELATION OF PITCH TO FREQUENCY

From the foregoing discussion it is evident that the frequency of a tone does not uniquely determine its pitch. Hence, in specifying the pitch of a tone, it is desirable to refer to the pitch of tones at some standard level of loudness. A convenient standard is the 40-db loudness-level (Fletcher, 3). It is customary to designate the pitch of a tone by the number of cycles per second (the frequency) of that tone, at the loudness-level of 40 db, which sounds equal in pitch to the given tone. This

procedure is a partial recognition of the fact that pitch is determined by the responses of living organisms to sound stimuli, but it has the defect of employing the numbers of the stimulus-scale (frequency) to represent an aspect of sensation (pitch). A desirable scale for the pitch of tones at the reference loudness-level (40 db) would be one expressed in numbers whose values are directly proportional to the magnitude of the perceived pitch.

One might suppose that the musical scale, which divides the range of audible frequencies into octaves, and these in turn into tones and semitones, would serve as a pitch scale. The musical scale, however, is inadequate, because two equal musical intervals in different parts of the frequency range do not constitute equal subjective intervals (see p. 83).

Our ability to construct a scale which will have the desired characteristic of representing the magnitude of perceived pitch by numbers proportional to that magnitude depends upon our ability to devise operations for the measurement of aspects of sensation. Controversy has for a long time centered upon the proposition that it is possible to measure the attributes of sensation, or to tell when one sensation is twice or three times as great as another. The truth of this proposition must depend, not upon *a priori* conceptions, but upon the outcome of experiment. There are, however, certain considerations pertaining to all sensory scales which we shall now digress to consider.

The Problem of Sensory Scales We devise scales for the purpose of facilitating the description of natural phenomena in terms of functional relationships, expressed, if possible, by the symbols of conventional mathematics. Scales, in other words, are constructed for a purpose. The intended use of a scale, then, becomes the most important factor in determining the criteria which the scale must satisfy in order to be considered adequate. In any particular case, we must first decide what sort of scale we want, and then determine by experiment whether or not such a scale can, in fact, be constructed. In other words, we must decide upon the criteria of the scale, and then devise operations for satisfying the criteria.

In the construction of sensory scales, the following considerations are particularly important

1 There are, in general, two types of scales. They may be designated as *intensive* and *numerical* scales. Scales which measure intensive magnitude enable us to place the things measured in a rank-order, i.e., arrange them according to increasing magnitude. Such a scale does not, however, enable us to say how many times one magnitude is greater than another, but only that it is greater. Numerical scales, on the other hand, have numbers which express the numerical relations between things measured. Thus when two magnitudes are measured in terms of a truly numerical scale, the scale numbers can be manipulated in accordance with arithmetical laws in order to determine additional relations, such as the sum of two magnitudes or the relative separation of two pairs of magnitudes.

2 These manipulations of the numbers on numerical scales have significance only if the manipulations correspond to a set of concrete operations which can be performed on the things measured. Otherwise, the validity of the outcome of the manipulations cannot be tested empirically. If, for example, we add a magnitude of 2 scale units to another magnitude of 2 scale units, and conclude that we have a magnitude of 4 units, our statements are of no empirical significance unless we have some concrete operations for adding the quantities that the scale measures in order to verify the result. The operations will, in general, be different for different things. Thus, the procedure for adding 2 meters to 2 meters to make 4 meters is very unlike that for showing that 2 henries of electrical inductance can be added to 2 henries to give 4 henries. Similarly, in the case of sensation we may reasonably expect to find that numerical scales are based upon operations peculiar to it alone.

3 Now, in psychological measurements, most scales have been scales of intensive magnitude from which rank-orders, but not numerical relations, could be obtained. What we should like to have are numerical scales—scales whose numbers represent some aspect of the response of a living organism to a class of stimuli, like sound.

4 The numbers on the numerical scale must be applied to the attribute of sensation (which is, of course, an aspect of an organism's response) in such a way that when they are manipulated according to the rules of arithmetic, one obtains a result which can be verified observationally. To the manipulations and to the results there must correspond a set of concrete operations. Since the basic operation for determining a sensory scale is that of presenting a stimulus to an observer and noting his response, the results of manipulating the scale numbers must, in general, be tested in terms of the 'experience' (response) of an observer. With such a scale the operation of addition might consist in changing the stimulus until the observer gives a particular response which indicates that a given relation of magnitudes has been achieved. In other words, a sensory scale is a scale of response, and the response of an observer who says 'this is half as great as that' is one which, for the purpose of erecting a subjective scale, can probably be accepted at its face value.

5 Although we could, for different purposes, choose any one of several sets of operations as defining the scale, that set will generally prove most satisfactory which leads to scale numbers bearing the most reasonable relation to the experience of the observer. A reasonable scale is one for which the number N stands for a sensation which does in fact appear to be half as great as that represented by the number $2N$, etc.

A Numerical Scale of Pitch On the assumption that observers are able to tell when one tone is half as high in pitch as another tone, a numerical scale of pitch has been constructed from determinations of the half value of the pitch of tones of several frequencies (Stevens, Volkman, and Newman). The observer was presented alternately with two tones at a loudness level of 60 db. One tone was fixed in frequency. The other could be varied in frequency by the observer until its pitch appeared to him to be half of that of the fixed tone. This procedure is called the *method of fractionation*. Ten different frequencies were used as the fixed tone. The five observers who took part in the experiment showed consistency in their

judgments, even though some of them had previously made the statement that pitch is not the sort of thing they would be able to cut in half. The judgment is apparently easier than one might suppose, especially if the observer does not become confused by the recognition of musical intervals when he sets the variable tone.

The geometric mean of the results of five observers is shown in Fig 25. This function tells us at what frequency the variable tone must be set in order that it shall sound half as high in pitch

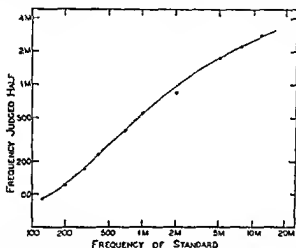


FIG 25 Showing the frequency of a tone (ordinate) which sounds half as high in pitch as a standard tone of another frequency (abscissa) (Stevens, Volkman, and Newman)

as the fixed tone. Hence, this function gives us the relationship that we need to know in order to construct a scale of pitch whose numbers are such that the number N stands for a pitch which sounds half as high as that represented by the number $2N$.

The pitch scale was constructed by assigning arbitrarily the number 1000 to the pitch of a 1000-cycle tone, and the number 500 to the pitch of the tone which sounds half as high, as determined from the curve in Fig 25, similarly for the pitch number 250, etc. By extending this procedure, we obtain the *pitch function* shown in Fig 26. This function expresses the relation between pitch and frequency, at a constant loudness-

level, and therefore it constitutes a scale of pitch satisfying the criteria laid down for it. This pitch-function has, within the limitations of the particular experimental procedure by which

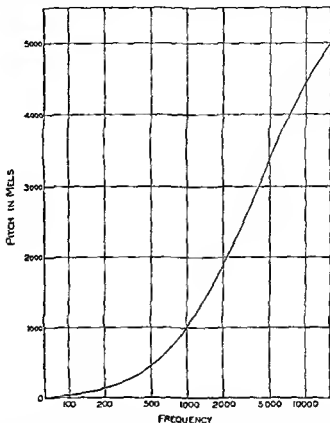


FIG 26 The pitch function This curve shows how the perceived pitch of a tone (measured in mels) changes as a function of the frequency of the stimulus. This pitch function was determined at a loudness-level of 60 db. (Stevens, Volkman, and Newman)

it was established, the numerical significance that the numbers on the pitch-scale are related to each other as the subjective magnitude of the pitches. The unit of the scale has been called a *mel* (from the root of the word *melody*). A pitch of 500 mels sounds twice as high as a pitch of 250 mels, provided "twice as high" is understood as being defined by the operations employed to establish the scale.

RELATION OF THE PITCH SCALE TO ALTERNATIVE PROCEDURES

The question arises concerning the possibility of verifying this pitch function by other procedures, such as bisecting tonal intervals, i.e., setting a third tone to a value halfway, in pitch, between two other tones. Such verification is theoretically possible—in fact, it is theoretically required, if the pitch scale is to be more than trivial.

The method of bisection has been applied to tonal intervals, but the results of different investigators have thus far been contradictory (Pratt, 1). Some workers have insisted that the bisection is made at the arithmetic mean, and some claim evidence for bisection at the geometric mean. A famous controversy was waged about this point (Titchener, 1). From the form of the pitch function in Fig. 26, it is evident that the point of bisection of an interval should depend upon the position of the interval on the frequency scale. It would be desirable to test the pitch function experimentally by the method of bisection.

In testing one function by another, we must, however, proceed cautiously to our conclusions. The ability of any two methods of bisection or fractionation to confirm each other is limited chiefly by the presence of constant errors in the experimental procedures (compare the case of loudness, p. 120). Some of the factors which may introduce constant errors are the size of the interval and its position on the stimulus scale, the order of presentation of the stimuli, the rate of presentation, the initial value of the variable stimulus (compare Geiger and Firestone), and the effect of what is known as "absolute judgment," namely, a tendency to adjust the variable tone to a value which is to some extent independent of the values of the limiting tones, but dependent upon preceding judgments. The final choice of a function to be used as a pitch scale will, therefore, be subject to revision whenever the sources of constant errors in the experimental procedures for fractionation can be detected and eliminated.

THE USES OF THE PITCH SCALE

Having established a tentative pitch scale we can use it to measure certain psychological magnitudes, and, by comparing it with physiological data, we can obtain information as to the probable basis of the judgment of pitch magnitudes. Some of these relations are treated elsewhere (see p 95 for measurement of the size of difference limens and p 97 for relation of pitch scale to basilar mechanics)

The Measurement of Musical Intervals An interesting application of the pitch scale occurs in the measurement of the subjective size of the musical intervals. We can measure the perceived size of various octaves by determining from Fig 26 how much the pitch changes from one octave to the next. In a similar way we can measure the size of other musical inter

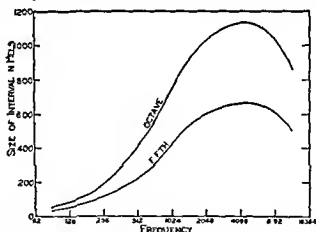


FIG. 27 Showing how the size of various musical intervals (measured in mels) changes as a function of the frequency of the geometric mean of the interval. The subjective size of different octaves may vary by as much as twentyfold (Stevens Volkmann and Newman)

vals. In general, the subjective size of any musical interval is proportional to the slope of the pitch function at the frequency which falls at the middle of the interval.

In order to illustrate these relationships, the subjective sizes of successive octaves and fifths, as measured in mels, is plotted in Fig 27. The plot for other intervals would be similar in form but different in ordinate value.

Quite definitely, musical intervals become subjectively larger as frequency increases up to the fourth octave above middle C (up to 4096 cycles). In other words, throughout the useful musical range, intervals increase in perceived magnitude with increasing frequency of the stimulus. This conception is not entirely novel. Stumpf decided that, in spite of the great difficulty of making these subjective comparisons directly, the upper octaves are perceptually larger than the lower octaves. Thus the pitch scale enables us to confirm Stumpf's judgment. Incidentally, these facts contradict the prevalent notion that "equal ratios of frequency give rise to equal intervals of pitch" (A. H. Davis, p. 235).

DIFFERENTIAL SENSITIVITY TO FREQUENCY

It is important for many purposes to determine accurately the minimal change in the frequency of a tone which can be detected by the ear. The size of the just noticeable difference in frequency determines the differential sensitivity, or the resolving power, of the ear. This minimal change in frequency is known as the *difference-limen* (DL). Strictly, the concept of differential sensitivity should be defined as the reciprocal of the DL. The size of a DL is a function of the frequency and the intensity of the tone, and is different for different observers. As in the case of the threshold of hearing, the concept of the DL is essentially statistical. Since the differential sensitivity of a living organism is in a continuous state of fluctuation, the ideal value for a DL would be that difference which is detectable by the organism 50 per cent of the time. This ideal is approximated in most psychophysical work (cf. Guilford for discussion of psychophysical methods).

The pioneer work on discrimination of frequency is associated with Preyer (1876), Luft (1888), and Meyer (1898). It was characterized chiefly by exceptionally small values for the DL (see Vance for historical summary). The next group of experimenters, Vance, Schaefer, and Stucker, agreed well with each other in determining DL's, but found them to be significantly larger than those of the pioneer workers (Vance). Two

representative sets of data are plotted in Fig 28, one for Luft and one for Vance. This plot is in terms of the *relative* DL—the ratio of the DL to the frequency at which it was determined. The early work can probably be criticized on the ground that extraneous cues for the identification of the lower or higher tone were not eliminated. It is particularly difficult to eliminate these cues when tuning forks are used as the source of sound.

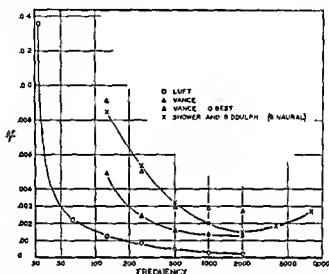


FIG 28 The various values of the relative difference-limen ($\Delta F/F$) obtained by various experimenters under different experimental conditions

Also, Luft used a different method (method of minimal change) and hence a different criterion for the DL from that employed by Vance, who used the method of constant stimuli. The selection of observers may also influence the size of the observed DL. Thus, if we average the results of the best ten out of Vance's fifty observers, we obtain results which in Fig 28 can be seen to lie well below the average for the fifty observers.

The first systematic determination of differential sensitivity to frequency by means of electrically generated tones was conducted by Knudsen (1), who obtained results in good agreement with those of Vance.

The shortcoming of all this early work is the fact that no single experimenter was able to measure DL's at all audible

frequencies and at all levels of intensity. It remained for Shower and Biddulph to make a more thorough investigation of differential sensitivity. They covered the frequency-range from 31 to 11,700 cycles at sensation-levels ranging from 5 db above threshold to the maximal level which the observer could tolerate at any given frequency. They used an essentially novel method, in order to minimize the effects of harmonics and of the transient frequencies which arise whenever a tone is turned on or off abruptly. A rotary condenser in the tuning circuit of an oscillator was so arranged that the observer could listen to a tone of unvarying pitch for a short interval of time. Then the frequency was changed sinusoidally to a new value, to which

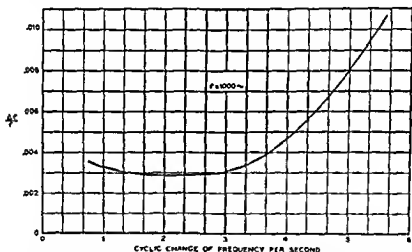


FIG. 29 The dependence of the relative difference limen ($\Delta F/F$) upon the rate at which the frequency of a tone is varied from the higher to the lower frequency. The difference between the higher and the lower frequency defines the value ΔF . (Shower and Biddulph.)

the observer listened for another short interval of time, whereupon the frequency returned, sinusoidally, to its original value. In other words, there was a smooth transition from one frequency to the other. The difference between the two frequencies was controlled by the separation between the plates of the rotary condenser, and the observer reported when this

difference was just large enough for the variation in pitch to be detected

Under this method the differential sensitivity of the ear becomes a function of the rate at which the frequency is varied. By controlling the speed of the rotary condenser, this function was determined, as shown in Fig 29. The best rate of frequency variation was taken to be 2 per sec.

The results plotted in Fig 28 are for binaural listening under the condition of Shower and Biddulph's experiment. Similar results were obtained for bone-conduction—a special case of

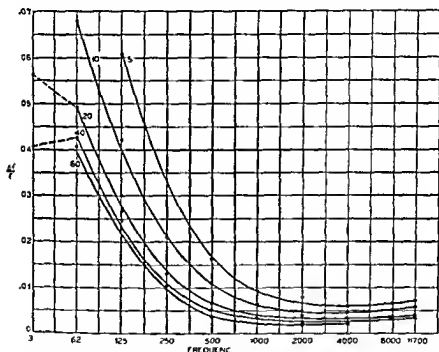


FIG 30 The dependence of the relative difference in frequency ($\Delta f/f$) upon frequency. The parameter here is sensation level as indicated by the numbers attached to the curves. (Shower and Biddulph)

binaural listening. For monaural listening, however, the relative DL's are larger than for binaural. In Figs 30 and 31, the results for monaural listening (averages from 10 ears) are plotted to show the effects of frequency and intensity on the relative DL. (See Table I for tabulated data.) At low fre-

quencies and at low intensities, the DL's are largest. This effect of intensity upon the size of DL's may well be due to the distribution and innervation of the hair-cells on the basilar membrane (see p. 275 and p. 369).

The marked rise in the curves of Fig. 30 at low frequencies is greater than that found by any previous experimenters, but it is precisely at these low frequencies that the effects of har-

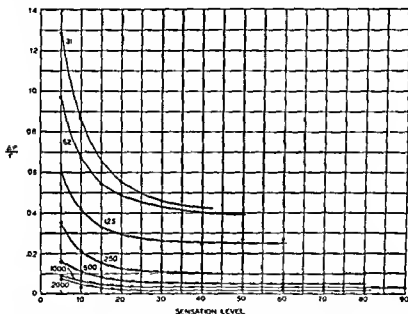


FIG 31. The dependence of the relative difference limen ($\Delta F/F$) upon sensation level. Here the parameter is frequency, as shown by the numbers attached to the curves (Shower and Biddulph)

monics and transients would be most effective in artificially lowering the DL. By repeating the experiment, using abrupt variation from one frequency to the other, much smaller DL's were obtained at low frequencies.

At frequencies above 500 cycles the *relative* DL's ($\Delta F/F$) are approximately constant. Below 500 cycles the *absolute* DL's (ΔF) are approximately constant, except for very low frequen-

cies At a point which lies in the vicinity of 45 cycles, the curves for the relative DLs show a point of inflection and tend to bend downward This tendency increases with intensity, and appears, therefore, to depend upon the introduction of aural (subjective) harmonics Since the second, third, etc., harmonics vary in frequency by an amount which is two, three,

TABLE I

The values of $\Delta F/F$ at various frequencies and sensations-levels These values are the averages of results from the ears of five men between the ages of 20 and 30 years The data were obtained at the Bell Telephone Laboratories (Printed by permission)

Sensation level	5	10	15	20	30	40	50	60	70	80	90
Frequency											
31	1290	0873	0702	0563	0438	0406					
62	0975	0678	0546	0491	0461	0426	0351	0346			
125	0608	0421	0331	0300	0266	0247	0270	0269			
250	0355	0212	0158	0130	0109	0103	0099	0098	0100	0107	
500	0163	0110	0081	0067	0055	0052	0042	0035	0042		
1000	0094	0061	0044	0039	0036	0036	0036	0034	0031	0030	0026
2000	0079	0036	0029	0021	0019	0019	0019	0018	0017	0018	
4000	0060	0044	0038	0031	0027	0023	0023	0020			
8000	0063	0051	0045	0038	0036	0029	0025				
11700	0069	0058	0042	0038	0036	0035	0030				

etc, times that of the fundamental, it is probable that at these very low frequencies the ear is detecting the variation of the harmonic rather than that of the fundamental

SPECTRAL ANALYSIS OF THE STIMULUS

In the preceding discussion, we accepted uncritically the naïve view that it is possible to change the frequency of a tone periodically from one value to another and back again, just as we might alternate the intensity of a light between bright and dim True, we have noted that the mode of transition from the lower to the higher frequency may influence the num

ber of transients created, but we have disregarded the fact that, no matter what the mode of transition, energy is scattered into other frequency regions. Even when the frequency is allowed to vary sinusoidally, the result is a sound with a complex spectrum, rather than a simple one. Change the frequency from 495 to 505 cycles and back again twice per second and we have precisely the equivalent of a set of steady tones spaced 2 cycles apart on each side of 500 cycles (see Chapter 9). These steady tones, or 'side bands,' enter the ear simultaneously and set up on the basilar membrane a pattern of stimulation. If the fibers of this membrane were very much more sharply tuned than they are, the ear would be able to respond separately to each of these individual tones, but, since the tuning is not sharp, the disturbances overlap and the tones beat with one another.

Now, how are we to understand the situation in the experiment of Shower and Biddulph? They found that, for 1000 cycles at 80 db above threshold, the just noticeable increment in frequency is exactly 3 cycles. In other words, when the two frequencies, 1000 and 1003 cycles, were presented alternately, with a sinusoidal transition from one to the other, at the rate of two alternations per second, the observer could just detect the effect. Of what, we may ask, did the stimulus actually consist from the point of view of its Fourier analysis? Plot *A* of Fig 32 provides the answer. It shows the approximate amplitude of the several components of the stimulus. These components are spaced 2 cycles apart and are symmetrical about the central component, whose frequency, in this instance, is 1001.5 cycles. These are actually the steady tones which we send into the ear when we modulate the frequency of a sound wave, after the manner of Shower and Biddulph. Nevertheless, the ear hears such a stimulus as an alternation between two pitches—an amazing effect which must be attributed to the fact that the components are close enough together on the basilar membrane to beat with one another. Each of the three major components sets into vibration a region of the basilar membrane, and we might represent the maximum amplitude of these forced vibrations by the solid curves of plot *B* in Fig 32. However, the

relative phases of these vibrations are constantly changing, because the frequencies are different. Consequently, there will be a time when the central and left hand components will reinforce each other, but will be out of phase with the component on the right. Then the effects will summate to produce a disturbance on the basilar membrane whose amplitude is represented schematically by the left hand dotted curve. At a later time the phases will combine in such a way as to give a result like the dotted curve on the right. At intermediate times the maximum of the disturbance will lie between the peaks of the two dotted curves, and it is the shifting back and forth of this maximum which provides us with the impression that the pitch of the tone is alternating between two just discriminable values. (These curves are only schematic, in order better to illustrate the principle, they are drawn much sharper than the actual peaks of the disturbance in the ear.)

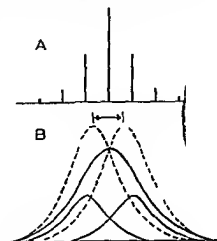


FIG. 32 Showing how the spectrum of a frequency modulated tone affects the basilar membrane. Plot *A* shows the spectrum of a 1000-cycle tone which is modulated by a just perceptible amount. Plot *B* demonstrates how the patterns of disturbance on the membrane due to the several components interfere and produce a composite disturbance which moves back and forth between the two positions occupied by the dotted curves.

Now, if we knew the exact form of vibration of the basilar membrane at all frequencies and intensities, we could determine the precise distance between the peaks of the dotted curves in Fig. 32, and this distance could be taken as the resolving power of the ear. In the absence of this knowledge, we probably do well to take the measured DL's as the best indication of resolving power. Nevertheless, while we are considering the experiment on differential sensitivity in terms of the spectra of the stimuli which produce a just noticeable difference, it is of inter-

est to examine some of these spectra. The spectra in Fig. 33 were constructed, from the data presented by Shower and Biddulph, by considering the transition from the higher to the

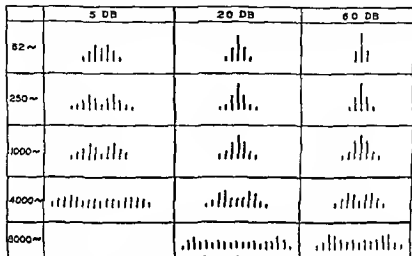


FIG. 33 The spectra of tones at various sensation-levels whose frequency is modulated by the amount needed to produce a just perceptible change in pitch. The frequency of the central component is indicated at the left. The rate of modulation was 2 per second and the components are spaced apart by 2 cycles.

lower tone as intermediate between the rectangular and sinusoidal forms (see van der Pol, 2, for analysis of these two types of modulation). These are, to a fair approximation, the spectra which, upon entering the ear, give the listener an impression of a tone which alternately changes in pitch by a just perceptible amount. Because the rate of alternation from the high to the low tone was 2 per second, the components of the spectra are spaced 2 cycles apart, and their relative amplitudes are proportional to the heights of the lines.

At the low intensity of 5 db above threshold, where the ear is relatively insensitive to small differences of frequency, the spectra are composed of more numerous bands, and the relative sizes of the outer bands are greater than at higher intensities of the same frequency. When the components are numerous the same principle applies as when there are only three—the suc-

cessive cancellation and reinforcement by the different components cause the point of maximal disturbance on the basilar membrane to move back and forth. For a given frequency of the central component, the excursion of this disturbance is greater when the side bands are distributed more widely. As the frequency increases, the spectra, as we should expect, grow wider, but there is very little difference in the spectra producing a DL at frequencies below 500 cycles. Even at frequencies below 100 cycles, where the spread of the disturbance on the basilar membrane is presumed to be quite extensive, the indications are that a spectrum of sound probably produces a DL through the operation of the same principles of reinforcement and cancellation as outlined for the case of a higher frequency.

Referring once more to the curve in Fig 29, we note that, with a 1000-cycle tone, a change of 3 cycles is just detectable, both when the alternation is made once and when it is made 3 times per second. Since the spectrum of a modulated sound depends upon both the rate and the range of the modulation, the spectra will appear quite different in these two cases. When the alternation is 3 times per second, the components are spaced 3 cycles apart, and their relative amplitudes are as pictured in plot *A* of Fig 34. When the rate is once per second, the separation between bands is only 1 cycle, and the relative amplitudes are as shown in plot *B*. These two rather different looking arrays of steady tones produce identical DLs, provided we define the DL as the total extent of the modulation, and presumably they do so in accordance with the same principle of reinforcement and cancellation. Owing to the beating of the various components, the maximal disturbance on the basilar membrane shifts back and forth through an equal extent for both spectra.

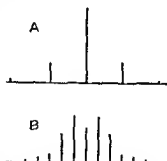


FIG 34 The spectra of a tone (1000 cycles) whose frequency is modulated by a just perceptible amount, at two different rates: 3 per second (plot *A*) and 1 per second (plot *B*).

A curious coincidence is the fact that the lowest value obtained for the *relative* DL for frequency is the same in both vision and audition. In both modalities the smallest ratio $\Delta F/F$ is very nearly 0.002. This suggests the question, "Does the alternate presentation of two different visual stimuli scatter energy to other frequencies?" Presumably it does. If we were to raise and lower, at a rate of 3 per second, the frequency of a single wave length of light (provided such could be obtained), the resulting stimulus would presumably have components spaced 3 cycles apart, but, although the ear can resolve tones separated by 3 cycles, we cannot hope that the eye could do so, because the DL for frequency in vision is of the order of 10^{12} cycles. The enormously high frequency of light would render trivial the effects of modulation. Therefore, the coincidence of values of the relative DL for frequency in both vision and audition does not depend upon the detection of the effects of modulation in both cases.

THE INTEGRATION OF DIFFERENCE LIMENS

The integration of the DL's for frequency serves many purposes. We may wish to know the total number of discriminable pitches in the range of audible frequencies, we may desire to measure the subjective magnitude of a DL by means of the pitch scale, or we may be interested in comparing the integrated DL's with certain physiological functions (see Chapter 15). The purpose of the integration will determine between what limiting frequencies and along what path we shall make the integration. The summation can, of course, best be made by graphical methods. When the ratio $F/\Delta F$, the reciprocal of the relative DL, is plotted against the logarithm of the frequency, the area between any two limits under the curve is proportional to the number of DL's between those two limits.

The Number of Discriminable Pitches On integrating along the reference level for pitch-comparisons (40-db loudness-level), between the limits of 20 and 12,000 cycles, we find that the ear can discriminate about 1400 different pitches. From present data we cannot extend the integration to 20,000 cycles,

but a reasonable extrapolation of the curves in Fig 30 makes it appear that between 20 and 20,000 cycles there are nearly 1500 discriminable pitches. Along the loudness-contour at the 60 db level the number of discriminable differences between 20 and 20,000 cycles is about 1800. At the 60-db level the number of distinguishable pitches is maximal and is approximately 3 times as large as the number at the very low level of 5 db.

The Subjective Size of Difference Limens for Frequency

The experimental procedure for determining the *objective* extent of a DL (in cycles) is such as to yield a measure of the resolving power of the ear, but it obviously does not provide for the measurement of the *subjective* size of the DL's. Discovery of the increment in frequency which is just noticeable, first at 200 cycles and then at 2000 cycles, does not disclose whether or not, at these different frequencies, just noticeable increments are subjectively equal in magnitude. Fechner assumed, quite arbitrarily, that, when two increments are both just noticeable, they are subjectively equal. Now, it is clear that two DL's are equal in the one respect of being both *just noticeable* (Boring, 2). But does this mean that they are also equal in respect of subjective magnitude? Since the operations for determining DL's are different from those for determining equal subjective magnitudes, we are not justified in assuming that DL's possess equal subjective magnitude until they have been compared in terms of a subjective scale.

If all DL's at a given loudness-level are of equal subjective magnitude, their integration should yield a function identical with the pitch function of Fig 26. This is equivalent to saying that, if all DL's are equal, the pitch arrived at by summing 100 DL's should appear half as high as the pitch obtained by summing 200 DL's. If we take the pitch function of Fig 26 as defining a numerical scale of perceived pitch, we can compare it to the integrated DL's, in the manner shown in Fig 35. The close correspondence between the pitch function (solid curve) and the function (solid squares) obtained from integrating DL's shows that, within the limitations of present measurements, all DL's for frequency are of equal subjective magnitude.

This relation is true, of course, only provided the DL's and the pitch-function are determined at a constant loudness-level. At other loudness-levels the pitch-function would need to be cor-

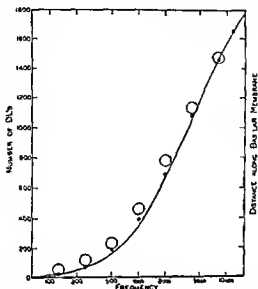


FIG. 35. The relation of the pitch function (solid curve) to the integrated DL's for frequency (solid squares) and to the experimental location of positions of vibration on the basilar membrane (circles). The ordinate scale (on left) shows the number of DL's as a function of frequency, when the integration is made at a loudness level of 60 db. The pitch scale in mels can be obtained by multiplying these ordinate values by the factor 2.83. The relative locations of positions of vibration on the basilar membrane are obtained by laying the linear extent of the membrane along the ordinate. Thus the ordinate scale on the right represents the relative linear extent of the membrane, in both man and guinea pig (Stevens, Volkmann, and Newman).

rected slightly in terms of the shift of pitch with change of intensity (Fig. 23). We could then compare the corrected pitch-function with an integration of DL's at the loudness-level of, let us say, 5 db. Such a comparison shows that, within the accuracy of the available data, all DL's at the 5-db level are also of equal subjective size.

How, then, do DL's at different loudness-levels compare? Since there are about 3 times as many discriminable pitches at the 60-db level as at the 5-db level, the DL's at the 5-db level

are about 3 times as large, subjectively, as those at the 60-db level. This relation is shown by the fact that, on integrating the first 100 DL's at 60 db, we arrive at a pitch of about 250 mels, whereas the integration of 100 DL's at 5 db brings us to a pitch of about 800 mels. In general, since the correction to be made in the pitch function when loudness-level is changed is slight, and since the integrations of DL's at various levels give essentially similar functions (differing only by a constant of proportionality), we may conclude that, as a first approximation, the relative subjective size (in mels) of DL's at different loudness-levels is given by their relative objective size (in cycles). Hence, from Fig. 30 we see that, as the intensity is increased, the subjective size of DL's must decrease. Above a sensation level of 60 db, however, the size remains essentially constant.

These relations between the subjective size of DL's for frequency are very different from those for intensity (see p. 148).

Relation to Basilar Mechanics On the assumption that to each audible frequency there corresponds a position on the basilar membrane 'tuned' to that frequency, it is interesting to note certain relations. In Fig. 35 are plotted circles representing, approximately, the positions of excitation along the basilar membrane (ordinate) as a function of frequency (Stevens, Davis, and Lurie). The similarity between the three functions, (a) position on the basilar membrane, (b) the pitch function, and (c) the integrated DL's, supports the original assumption of Wegel and Lane to the effect that any two tones are just discriminable in pitch when they stimulate two areas of the basilar membrane separated by a certain constant distance.

The correspondence of these functions suggests another interesting hypothesis. Apparently, when an observer is asked to set a second tone to half the pitch of a given tone, he changes its frequency until it stimulates a position on the basilar membrane midway between the position stimulated by the given tone and the apical end of the membrane (Stevens, Volkmann, and Newman). He is, of course, not aware of these locations as such, but the underlying physiological process which makes comparison of pitches possible seems to be characterized chiefly

by spatial differentiation. Although there are subsequent central nervous processes, the form of certain discriminatory functions is evidently imposed by the receptor mechanism.

THE PITCH OF COMPLEX SOUNDS

Although we define the concept of pitch in terms of the perception of pure tones, it is clear that noises and other aperiodic sounds may have a more or less definite pitch. In general, the pitch of a complex sound depends upon the frequency of its dominant components. Thus we find that when observers are asked to designate the pitch of a tonal mass composed of numerous frequencies, all lying within a restricted band, the observers name a pitch which is close to the center of the band (Ekdaahl and Boring). Of course, the pitch of a noise, or of a tonal mass, is more or less indeterminate, depending upon the range of frequencies present.

The most extremely complex sound is that commonly called *thermal noise*. This is the noise heard when the voltage due to the random motion of electrons in an electrical resistance is amplified and impressed on a loud speaker. Provided the amplifier and speaker have uniform characteristics, the resulting noise contains all audible frequencies at equal intensity. It sounds much like a hiss or a *shhh*. Of course, the ear does not distinguish the presence of any of the individual frequencies in the continuous spectrum of this noise, but when any band of frequencies is eliminated by means of electrical filters, a striking change occurs in the sound. This fact shows that those frequencies which were filtered out had their effect in the total noise. As might be expected the pitch of thermal noise is quite indeterminate. However, the observer is not aware of any extremely low or extremely high characteristics. Frequencies of the middle range—1000 to 5000 cycles—appear to dominate the sound. Since the ear is most sensitive throughout the middle range, these components are the ones, in a thermal noise, which are most effective in producing stimulation, and hence are most effective in determining pitch.

When the number of components in a sound are few enough in number, the ear can resolve the complex into its individual

frequencies. Thus a trained observer can discriminate the upper partials of a vibrating piano string, or pick out the individual instruments in a symphonic chord. The fact that the ear resolves a complex tone into its components is known as Ohm's acoustic law. Presumably this capacity depends upon an ability to discriminate the separate areas of excitation on the basilar membrane. When the areas are too numerous, however, or overlap too much, resolution fails.

THE CASE OF THE MISSING FUNDAMENTAL

Whenever a complex tone is composed of frequencies differing by a constant amount of 100 cycles or more, the apparent pitch of the complex mass is not the mean of the component frequencies, but is that of a tone whose frequency is equal to the constant difference (Fletcher, 3). Thus, when the component frequencies 700, 800, 900, and 1000 cycles are sounded together, the pitch is judged to be that of a 100 cycle tone. When the components 400, 600, and 1000 cycles are sounded, the pitch appears to be that of a 200-cycle tone. It is possible, then, to demonstrate a paradoxical phenomenon. When to the combination of 400, 600, 800, and 1000 cycles the tones 500, 700, and 900 cycles are added, the pitch appears to drop by precisely an octave. In other words, under these special conditions, the addition of pitches, each of which is higher than the apparent pitch of the complex, may result in a lowering of the perceived pitch of the ensemble.

These facts make comprehensible the striking experiment in which the fundamental frequency of a musical note is removed by selective filters without changing the apparent pitch of the note. Since the harmonics present in the note differ by a constant amount, namely, an amount equal to the frequency of the fundamental, the harmonics alone are sufficient to determine the pitch of the note. Even when all the frequencies below a certain value—300 cycles, for example—are removed from a musical selection, the quality of the music is altered to an astonishingly small degree. The Bell Telephone Laboratories have developed phonograph records illustrating these phenomena.

RELATION OF PITCH TO DURATION

The foregoing laws of pitch perception relate to sounds presented for a second or more. What happens, then, to pitch when the duration of sounds is reduced to smaller and smaller values? Clearly, in the limiting case, when only one cycle of a tone is presented, one hears a click rather than a tone. It might be urged that a click has no pitch, but, on the other hand, casual observation shows that some clicks sound higher than others. A systematic problem would be to determine whether a single wave taken from a 1000-cycle tone sounds higher in pitch than a single wave taken from a 500-cycle tone. The wave from the higher tone would represent a sharper pressure gradient, or a steeper wave front, and might well give rise to the perception of a higher pitch when the two waves are directly compared (see p 282).

A related problem is the determination of the number of cycles required for a tone to be perceived as having a definite tonal quality. Historically this problem has been phrased as though a single answer were possible—as though a tone lost its pitch quite suddenly when the duration was reduced to a certain small value. Actually, however, as the duration of a tone is decreased, several changes take place. More specifically, if we begin by presenting a 1000-cycle tone for a very brief period, say 2 or 3 msec, and then increase the tone's duration, the sensation passes through three principal stages. First, one hears a nearly toneless click which seems to be without pitch. Second, the sound acquires a more or less definite pitch, although the click remains one of its prominent aspects, but this apparent pitch is different from the pitch of the same frequency sounding for a longer time. Finally a duration is reached at which the pitch can be ascertained without the constant error typical of the second stage.

As we have already seen, when the tone is in the first stage and is 'pitchless' closer observation may reveal that it has some degree of pitch, that is to say, a listener may be quite certain that the tone is higher or lower than some other tonal standard. Whenever such comparisons can be made, we have a method

of assigning a pitch to a sound, even though the range of uncertainty may be large

In the second stage, where the duration is of the order of 10 msec, the pitch, although growing more definite, is clearly lower than for longer durations. One claim has been made that the pitch of high tones is lowered by shortening their duration, but that the pitch of low tones is raised (Burck, Kotowski, and Lichte, 2). An experiment now in progress seems to show, however, that the apparent pitch of all tones (at least from 250 to 8000 cycles) falls with shortened duration (Ekdahl and

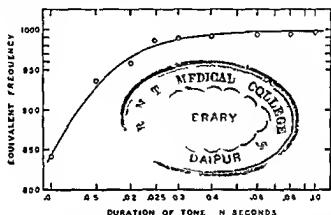


FIG 36 Showing how the pitch of a tone changes as a function of its duration.

The ordinate shows at what frequency a tone lasting 1.5 sec sounds equal in pitch to a 1000-cycle tone presented for the period of time indicated by the abscissa. Example a tone of 1000 cycles lasting 0.01 sec sounds equal in pitch to a tone of 842 cycles lasting 1.5 sec. Each point represents the average of 60 observations by a single observer (Ekdahl and Stevens)

Stevens) Fig 36 shows the course of pitch as a function of the duration of the stimulus

The line between the second and the third stage is not sharp, and it varies from person to person. Burck, Kotowski, and Lichte tested several people and found as typical the results plotted in Fig 37. The absolute time necessary for the identification of the pitch of a tone is smallest in the middle range of frequencies, where it is approximately 0.01 sec. The number of sound waves in these tones can be found, of course, by multiply

ing the frequency by the duration, and we find that from 3 to 4 waves are required to specify the pitch of tones below 200

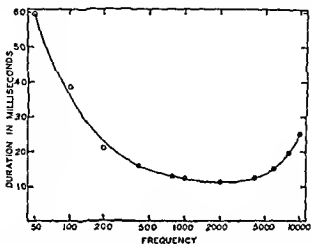


FIG. 37. Showing how long a tone of a given frequency must last in order to produce the experience of a definite pitch, according to the criterion used by Bärck, Kotowski, and Lichte (2)

cycles. At 1000 cycles about 12 waves are needed, and at 10,000 cycles the number jumps to about 250.

Now, the points in Fig. 37 show the time a tone must last

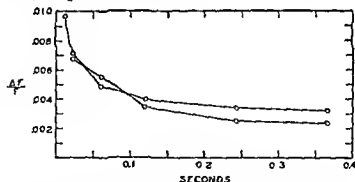


FIG. 38. The dependence of the relative difference limen ($\Delta F/F$) upon the duration of a tone (800 cycles). The curves are for two observers (After Békésy, 4)

in order for its pitch to be perceived, only provided we accept a certain criterion for what we mean by perception. The crite-

nion used in this case was arbitrary, but acceptable for the purpose in hand. From another point of view, the proper measure of the presence or absence of pitch in a tone is the precision with which the pitch can be identified. Since our measure of precision in sensation is the DL, we might inquire into the effect of duration on the DL for frequency discrimination. Data in this field are scant, but Bekey (4) presents the results, for two observers, as shown in Fig. 38. These curves demonstrate clearly that the loss of pitch occurs gradually as the duration of the tone is shortened. Some pitch would remain, according to this criterion, just as long as the DL is small enough to be measurable.

At this point, we might profitably turn to an analysis of what a short tone actually consists, with regard to its sound spectrum. We have already seen the advantage of the type of analysis which shows us that, whenever we alter the frequency of a tone for the purpose of measuring DLs, we introduce additional frequencies and create thereby a complex spectrum. The same relation is true of the mere turning on and off of a tone—we complicate its structure by so doing. A single pure tone sounding throughout eternity would have a solitary frequency in its spectrum, but a tone lasting for any finite time has an infinite number of frequencies in its spectrum. Fortunately, all these frequencies do not have the same amplitude. Only when the sound lasts an infinitely short time is the spectrum uniform throughout, and its frequency, therefore, completely indeterminate. As the duration is increased, the band of the spectrum containing most of the sound energy narrows in width, and when, as we have seen, the duration is infinite, the spectral band is infinitely narrow. These notions are inherent in the *principle of uncertainty* as it has been developed in physics, and they apply to any periodic phenomenon. From the principle of uncertainty we conclude that the accuracy with which the frequency of a sound can be determined is proportional to its duration. Stated symbolically the principle is

$$\Delta f \Delta t = 1$$

where Δf is a measure of the width of the main peak of the spectrum, in cycles, and Δt is the duration of the tone (Stewart, 4)

As an example of the spectral distribution of the amplitudes of the component frequencies in an 800-cycle tone whose duration is but a single period ($\Delta t = 1/800$ sec), consider Fig 39 (Bürck, Kotowski, and Lichte, 5) The maximal amplitude

FREQUENCY

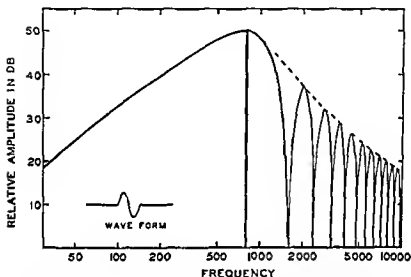


FIG 39 The spectral distribution of the energy in a wave consisting of a single cycle out of an 800-cycle tone. The wave lasts $1/800$ sec and the energy is distributed in continuous bands spaced apart by 800 cycles (After Bürck, Kotowski, and Lichte, 5)

occurs at 800 cycles, and the width of the main band, at an amplitude equal to one half the maximal amplitude (44 db), is also 800 cycles ($= 1/\Delta t$). Other continuous bands containing higher frequencies occur at intervals of 800 cycles, but their amplitudes fall off with frequency as shown by the dotted curve.

Now, when the ear is required to ascertain the pitch of a very short tone, it must resolve a continuous spectrum whose effective width is inversely proportional to the duration of the tone. Obviously, neither the ear, nor any other frequency-analyzer, can assign a pitch to a continuous spectrum, except to

say that it lies somewhere within the spectrum. We can, however, refer to the curve in Fig. 37 and calculate the form of the spectrum which just yields a sensation having a definite pitch, according to the criterion used. Such calculations show that the pitch of a tone is detectable when 70 per cent of the energy in the spectrum lies between ± 5 per cent of the principal frequency (Burck, Kotowski, and Lichte, 7). But, if we adopt a more liberal criterion for deciding whether a brief tone has pitch, the spectral distribution of frequencies may be much wider without making the pitch completely indeterminate.

THE THRESHOLD OF SUCCESSIVENESS

One additional fact relating to the duration of tones should be mentioned here. Experiments have been carried out to determine by how much the onsets of two tones must be separated in time in order for them to appear successive rather than simultaneous (Strecker, Burck, Kotowski, and Lichte, 3). The practical problem arises in telephone communication. When two

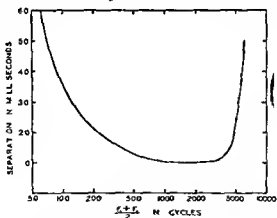


FIG. 40 The just detectable temporal separation in the onsets of two tones (F_1 and F_2). If the time interval for a given average frequency $\left(\frac{F_1 + F_2}{2}\right)$ is shorter than the value on the ordinate only a single onset is experienced; if the interval is longer one hears two successive onsets. (After Burck, Kotowski, and Lichte, 3.)

different frequencies are sent over a long transmission line, one of them may be retarded more than the other. Obviously, if

the frequencies in a speech wave are retarded unequally by large enough amounts, intelligibility may suffer. Hence, it is important to know within what limits the ear will tolerate successiveness in the onsets to two sounds.

The curve of Fig. 40 shows the just-detectable difference in time of onset for two tones of different frequency. The two tones were chosen so that the relation between their frequencies was always $F_2 = 1.1 F_1$. The average of the two frequencies is plotted along the abscissa.

The chief item of interest in Fig. 40, according to Burck, Kotowski, and Lichte, is that the times involved are rather similar to the time required for the recognition of the pitch of a tone. In other words, if the first tone sounds long enough for its pitch to become established in the ear of the listener before the second tone begins, the tones will appear successive. If the time between the tones is insufficient to establish the pitch of the first before the second tone arrives, the onsets will appear simultaneous.

Or, we might consider another, but related, aspect of the phenomenon. Common experience with electrically generated tones demonstrates that, whenever a tone is switched on suddenly, a sharp click is heard. The same is true when a tone ends abruptly, and the effect is usually not due to faulty switching, but to the generation of transient vibration. Now, if the transients due to the onset of the first tone overlap sufficiently those arising from the second tone, the tones will seem to begin simultaneously and to be accompanied by a single click. In order to achieve succession, the two clicks must not overlap enough to fuse into a single click.

Of course, if the tones are turned on gradually, rather than abruptly, the threshold of succession is raised, as we might expect, and a longer separation is required to avoid the experience of simultaneous onset. Here the beginning of the tones is not so sharply defined as when the transient click is fully developed.

ABSOLUTE PITCH

Many conflicting claims are made regarding the ability of certain persons to name precisely the pitch of a musical note without the aid of a standard of reference. Some people claim to recognize middle C, for example, at any time and any place. The evidence for this ability is mostly at the anecdotal level, however, because systematic controls are difficult. What we should like to mean by absolute pitch is the ability to name the pitch (or the frequency) of a *pure* tone without the aid of such devices as whistling or humming the note, i.e., without the aid of the kinesthetic cues involved in the reproduction of the tone. We should test the observer with pure tones, because complex tones, such as those produced by musical instruments, have distinctive qualities which may be readily recognized. Thus, for many musicians, absolute pitch reduces to an ability to name notes played on one particular instrument.

Nevertheless, some persons undoubtedly possess a genuine ability to recognize pitch which far exceeds the ability of the average individual. In fact, a most striking feature of this elusive gift, held so much in awe by the musician, seems to be its extreme variation among different individuals. How extreme this variation is among a large group of listeners, under controlled conditions, would be interesting to determine. Perhaps people differ less than has been supposed.

Several investigators have attacked the problem of the extent to which relatively untrained observers are able to acquire absolute pitch. A recent study (Wedell) has confirmed previous demonstrations that relatively unmusical observers can learn to increase their accuracy in assigning pitch numbers to pure tones. The greatest increase in ability takes place during the first few practice sessions, after which an indefinite plateau is reached. This plateau represented, for four observers, an average error about one half as large as that present at the beginning of the experiment. Apparently, in learning to recognize the pitch of tones in a given range, the observers do not learn individual notes, but rather they build up a more or less cohesive subjective scale in terms of which they judge the place

ment of notes within the range. Hence, in this type of absolute pitch, the judgment is, at least in part, one of relation.

Unlike the case of hue in vision, the pitch scale is not marked by critical points to which the usual observer can anchor his judgments. The primary hues provide more or less sharply defined points in the visual spectrum, which are readily recognized (Westphal), but which have no counterpart in the auditory spectrum. Pure spectral green marks a definite transition between colors which are yellowish and colors which are bluish. Middle C, however, is one tone in a homogenous continuum unmarked by qualitative turning points. It is perhaps for this reason that absolute pitch must be regarded as a rare gift.

Many musicians, however, do not agree that the musical scale is completely lacking in such qualitative turning points as characterize the scale of hues. Bachem insists that there is about the note C a certain "tone-chroma"—a certain "C-ness"—which is the same for the note C in all octaves, and which is unlike the chroma of the note D. This aspect of tones is presumably the same as what has sometimes been referred to as *tonality*, and its recognition is claimed by some to be the cue to absolute pitch.

Bachem studied ninety cases of "genuine absolute pitch." He reports that seven persons in this group "possessed infallible absolute pitch over the whole scale of the piano and for all musical instruments and physical apparatus with which they were tested." Not even errors of half tones or octaves were observed. The judgment was immediate and definite, and possessed a high degree of subjective certainty. These people claimed to base their decision upon the immediate perception of tone-chroma, and to rely upon a recognition of the "height" of the tone for the identification of the particular octave to which the tone belonged.

Forty four persons had infallible absolute pitch, provided we neglect the following types of errors:

1. Confusion between octaves
2. Constant errors of a half tone in one direction. (These errors may be due to the fact that there are several standards

of pitch in use, i.e., A is not always taken as 440 cycles)

3 Errors of a half tone downward in the highest part of the musical scale, and of a half tone upward in the lowest part (These errors are so common that they all but represent the rule)

In addition, eight persons had good absolute pitch over the limited range of three to four octaves. This type may be called "regional" absolute pitch. Five showed excellent ability on certain instruments, but not on others. Seven could identify the pitch only within a limited range on certain instruments. Absolute pitch in these cases appears limited to the recognition of timbre. The remaining nineteen persons showed fair ability in the identification of pitch, but made many errors and were slow and indecisive in their judgments.

Some people possess what Bachem calls "quasi absolute pitch." They know, for example, the lowest note they can sing, and, by applying a knowledge of musical intervals, they can estimate the pitch of another tone to within one or two semitones. The judgments are accompanied by much singing and humming, and usually take much more time than the judgments of those possessing "genuine absolute pitch." The recognition of pitch is also called quasi absolute when the person relies upon a memory of a specific note with which he is very familiar, and tries to estimate the interval between this note and the unknown tone.

CHAPTER 4

LOUDNESS

Just as we found it necessary to distinguish between pitch and frequency, so must we discriminate sharply between the meaning of the concepts *loudness* and *intensity*. We use the word *intensity* to mean the magnitude of a sound as measured with the aid of instruments and expressed in terms of energy or pressure. *Loudness* refers to an aspect of the sensation obtained by listening directly to a sound. We measure loudness by means of the discriminatory responses of a normal human observer.

Although loudness and intensity bear no simple relation to each other, the acoustical literature abounds with statements implying their synonymy. Loudness is *not* our perception of intensity, and the decibel, contrary to what is sometimes assumed, is not a unit of loudness. The decibel is a stimulus unit expressing the relation between *two* intensities. Thus confusion arises when experimenters express their measurements in decibels, but fail to indicate to what the decibels refer. A decibel is a measure of the ratio between two physical quantities (see Glossary) and is, therefore, ambiguous unless one of the quantities is stated explicitly. The statement that a sound has an intensity of 50 db has meaning only when we know to what the 50 db are related, i.e., what zero db is. (See Appendix III for a table of decibels.)

The following are the most common scales for expressing the intensity of a stimulating sound.

1 *Intensity-level* indicates the number of decibels that the intensity of a free progressive sound wave is above the arbitrary *reference intensity*. On this scale:

zero db = 10^{-12} watt per square centimeter

zero db = 0.0002 dyne per square centimeter

zero db = 73.8 db below 1 dyne per square centimeter

2 *Sensation-level* indicates the number of decibels that a

sound is above the threshold of hearing at that frequency. Sensation level can be translated into intensity level provided we know the intensity of the sound at threshold, or provided the observer's hearing is normal and his threshold comparable to the curves of Fig 17. Sensation level provides a convenient scale for expressing the results of experiments in which it is impracticable to measure the absolute intensity of the sound, but in which the reduction in intensity necessary to reach the observer's threshold can be determined.

3 *Loudness-level* for a given tone is defined as the intensity level of a 1000-cycle tone which sounds equal in loudness to the given tone. For a tone of 1000 cycles, called the *reference tone*, intensity level and loudness-level are equivalent. For other tones, loudness-level may be determined by the procedure outlined below (see p 123). It has been proposed (Fletcher and Munson, 1) that the reference tone be defined as a plane or spherical sound wave having only a single frequency of 1000 cycles and listened to by an observer facing the source. The intensity level would then be the number of decibels that this sound is above the reference intensity, which must be determined for the sound field at the position where the listener's head is to be placed*. There is some possibility that the German word *phon* will come to be the accepted name for the unit of loudness-level. The definition of a phon is mathematically the same as that of a decibel, and, hence, whenever we refer to loudness-level we may substitute the word *phon* for the word *decibel*.

* This definition of loudness-level presupposes a free progressive sound wave to which the observer listens with both ears. Actually, the determinations of loudness-level available at present were made with receivers on the ears and the intensity of the 1000-cycle reference tone was stated in terms of its sensation level (see Fig 44). This procedure is the more practical. Hence most often when we shall have occasion to refer to loudness-level we shall mean the loudness of a 1000-cycle tone whose intensity is a certain number of decibels above its threshold as determined under the actual conditions of listening. Until certain experimental discrepancies between field and pressure measurements have been resolved, we shall have to content ourselves with this inconsistency between the formal and the practical definition of loudness-level. (See p 125)

None of these three scales is a loudness scale. Each is a measure of the intensity of the stimulus relative to some arbitrary physical standard. The establishment of a numerical scale to represent the psychological magnitude, loudness, provides a problem similar to that discussed in connection with the pitch scale (see Chapter 4).

CRITERIA FOR A LOUDNESS SCALE

In creating a loudness scale we should like to satisfy two conditions. First, our scale should be applied to the attribute of sensation in such a way that the numbers on the scale have true numerical significance, which means, simply, that, if the numbers are manipulated according to the rules of arithmetic, the result (and the manipulations) correspond to a set of physical operations. Second, our scale should bear a reasonable relation to the experience of the observer. Thus, the scale would be satisfactory if the magnitude of the attribute of sensation to which the number 10 is assigned should appear to be half as great to the listener as that to which the number 20 is given, and twice as great as the magnitude to which the number 5 is given.

A scale, then, which would enable us to designate the *numerical* relation between magnitudes of the attribute loudness can be constructed by assigning some number N to a given magnitude, and the number $N/2$ to the magnitude which appears half as great to the experiencing individual. Obviously, in the application of this criterion we are limited by our ability to devise operations for the determination of fractional magnitudes of sensation. Three general methods have been used to discover the intensity at which one tone sounds half as loud as another tone.

FRACTIONATION OF LOUDNESS

1. The observer is required to make a direct estimate of the fractional relation between two tones sounded successively. Several variations of this procedure are possible, and several

experimenters have contributed data on the fractionation of loudness

The work of Richardson and Ross appears to be the earliest published. Their observer heard tones of two different intensities and was required to rate one of the tones as a certain fraction or multiple of the other. Unfortunately, the intensities of the stimuli were not reported in terms of acoustical quantities, so that comparison with later results is difficult. Nevertheless, Churcher, by making reasonable assumptions, was able to demonstrate that the data of Richardson and Ross are

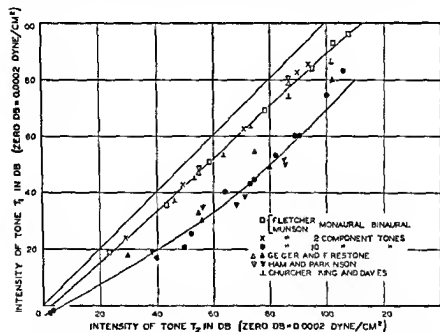


FIG 41 The ordinate shows the intensity at which a tone (T_1) sounds half as loud (open figures) or a tenth as loud (solid figures) as another tone (T_2) whose intensity is given by the abscissa

in good agreement with more recent results. These authors cite Stumpf's objection that "one sensation cannot be a multiple of another. Every sensation presents itself as an indivisible unit." Although this assertion may be true, it does not follow that we cannot establish scales of loudness, for loudness must be regarded as a measurable *aspect* of sensation. Sensa

tions themselves cannot be divided, but the numbers representing the magnitude of one of their aspects can

Ham and Parkinson produced tones with a loud speaker and asked observers to estimate the fractional reduction in loudness attendant upon a known reduction in the intensity of the stimulus. From their results it is possible to determine the intensity at which one tone sounds half as loud as another. These results for a tone of 1000 cycles are shown in Fig 41, where we find the intensity of a tone T_1 which appears to be half as loud as the tone T whose intensity is given by the abscissa

In the experiments of Geiger and Firestone the test tone was presented to the observer by means of telephone receivers applied to both ears, and he was required to change the intensity of a second tone until its loudness was a certain ratio of that of the test tone. The ratios employed were 0.1, 1, 2.5, 5, 10, 20, 40, 100. Frequencies of 1000 and 60 cycles and a complex tone were tried. The results for the 1000-cycle tone, in which the second tone was set to half the loudness value of the test tone, are also shown in Fig 41. These experimenters found that the order of presentation of the tones to be compared may influence the results.

The experiments of Churcher, King, and Davies were carried out mainly with pure tones of 800 cycles. Their observers were asked to set a second tone to a value of loudness equal to one half and to one fourth of the loudness of a standard tone. These results are also shown in Fig 41. Very nearly the same result was obtained from two successive halvings as from a single quartering.

It is clear from Fig 41 that satisfactory agreement can be obtained from direct subjective estimates of loudness. This method of direct estimate is necessarily the most fundamental (although not necessarily the most reliable) one under the criteria previously laid down for the nature of the loudness scale. The other methods are also valid in so far as they offer alternative ways of getting the same results.

2. An alternative method, offering the possibility of greater

reliability, makes use of the fact that the two ears are connected in such a way that a tone introduced into one ear sounds half as loud as the same tone introduced into both ears. The procedure, then, is to have the observer adjust the intensity of a tone in one ear until it sounds as loud as a given tone in both ears.

Such monaural-binaural equations have been carried out by Fletcher and Munson (1), whose results are presented in Fig. 41. It is only because of the agreement between these data and those procured by direct estimate that we are able to conclude that loudness sums in the two ears.

3. Another method, proposed by Fletcher (4), is based on the fact that two tones of equal loudness, which are sufficiently separated in frequency as not to stimulate overlapping areas on the basilar membrane, yield, when presented together, a loudness twice as great as either one alone. By equating a third tone first to one and then to both, we should obtain the ratio of intensities corresponding to a ratio of two to one in loudness. Here again validation of the method depends upon its ability to produce results comparable to those obtained by direct estimate. That such agreement is forthcoming can be seen from the data for two-component tones in Fig. 41.

If the tones introduced into the same ear are too near in frequency, they stimulate overlapping areas of the basilar membrane, whereupon some degree of masking may occur and may interfere with the summation of the two loudnesses. Strikingly different, however, is the effect when the two tones are led to each ear separately. In this case, summation occurs, but only when the frequencies are close together. Thus Fig. 42 (Békésy, 4) shows the relative intensity (sound pressure) of a third tone sounding in one ear and equated to the combined loudness of two tones sounding simultaneously, one in each ear. Since the two tones had an intensity 40 db above threshold, the results for the case in which they were of the same frequency (zero on the abscissa) check with the data of Fig. 41. When the two tones are of different frequency, and are led to the two ears separately, loudness does not sum. It appears that, in order for

loudness to sum arithmetically in one ear, the tones must be far apart in frequency—for it to sum in two ears separately, the tones must be identical in frequency. Of course if the tones in one ear are identical in frequency and phase, their intensities must sum. In fact Békésy (2) has presented a curve similar to

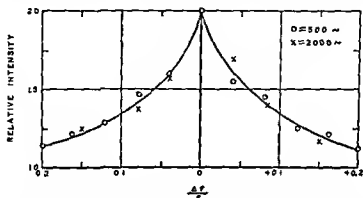


FIG 42 Showing the relative intensity (sound pressure) of a comparison tone equated in loudness to a pair of tones presented dichotically (one in each ear). Here we see that the loudness due to a tone F increases when another tone, $F \pm \Delta F$, is led to the other ear, although the increase is not the same for all values of ΔF . The sensation level of F and of $F \pm \Delta F$ was 40 db. (After Békésy, 4)

Fig 42 obtained with one ear. (This result of Békésy's is in apparent conflict with Fletcher's finding.)

Related to the problem of summation in the two ears is the observation (Stevens and Sobel) that, in the case of binaural beats (see p 172), the apparent loudness is greatest at the instant when the tones in the two ears are exactly in phase.

Ratios of loudness other than two-to-one can be established by varying the number of equally loud components, provided they can be kept far enough apart in frequency to prevent masking. Data for a tone of ten components (Fletcher and Munson, 1) are shown in Fig 41. The tone consisted of ten harmonic frequencies with a fundamental of 530 cycles. Each component was generated by an optic siren and its intensity was adjusted so that its loudness was equal to that of a 1000-cycle tone whose intensity is shown by the ordinate of Fig 41. The

1000-cycle tone was then equated in loudness to the ten component tone, at which point its intensity was as shown by the abscissa. These results should be compared to those obtained from observers who made direct estimates of the ratios at which two intensities gave a tenfold difference in loudness (see Fig 41). As we should expect, the agreement is less than was found for the determination of a twofold difference, but, in view of the nature of the judgment, Fletcher thinks it remarkable that the two kinds of data determine a single curve, within what he terms "observational error." The consistency between the data for twofold and for tenfold fractionation is discussed below.

THE LOUDNESS FUNCTION

From the data in Fig 41 we can proceed graphically to define an intensive function satisfying the criteria laid down for an acceptable loudness scale (compare the procedure for erecting a pitch scale, Chapter 3). This function is the one whose value at any given intensity is proportional to the subjective loudness produced by a tone of that intensity. First, we fit a curve to the data obtained by the 'halving procedures,' giving special weight to the points determined by the monaural binaural method. Then we assign the arbitrary number 1 to the intensity of 40 db above threshold and read on the ordinate scale the intensity of the tone which sounds half as loud, and which, therefore, receives the number 0.5. After repeating this procedure both above and below our starting point at 40 db, we can plot the function for the 1000 cycle tone, as shown in Fig 43. This function, then, satisfies the criterion that any value N stands for a tone which appears to a normal observer half as loud as that represented by the number $2N$ —at least within the present limits of experimental error. Had we used, in an analogous manner, the curve in Fig 41 representing a tenfold reduction, we should have obtained a very similar function. In fact, the striking agreement (see Fletcher, 4) between the functions derived from the twofold and from the tenfold fractionations probably justifies a high degree of confidence in our ability to establish a meaningful loudness scale.

The convenience and utility of such a loudness-scale makes it seem appropriate to select and name a fundamental unit of loudness. The loudness of a 1000-cycle tone 40 db above thresh-

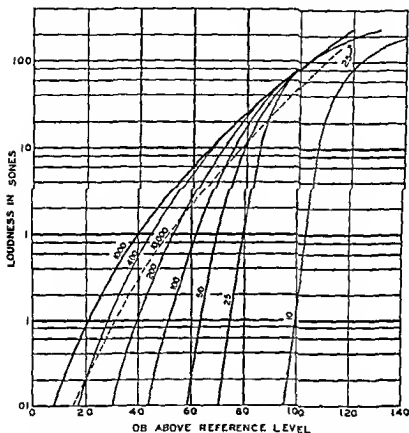


FIG 43 The loudness function Showing how the perceived loudness of various tones depends upon the intensity of the stimulus. Frequency is the parameter.

old, listened to with both ears, recommends itself as the logical unit, because 1000 cycles has been selected as the reference-frequency for loudness-comparisons leading to the determination of *loudness-level*, and the loudness-level of 40 db above threshold has been proposed as the reference-level for determining the *pitch* of a tone (see p 76). Such a unit should prove

to be of the right order of magnitude for general usefulness, since it is only about one third of 1 per cent of the maximal loudness the ear can support. As we shall see later (Fig 62, p 151), this unit corresponds in order of magnitude to the differential thresholds of moderately intense tones of the musical scale. As a name for the unit the word *sone* has been proposed (Stevens, 7)

Although an empirical formula relating the loudness of the 1000-cycle reference tone to the intensity of the stimulus would be a great convenience, the function of Fig 43 does not lend itself to simple mathematical expression. On the assumption that the loudness-function can be represented by a straight line for intensities above 40 db (Fletcher, 4), and that for low intensities loudness is proportional to the intensity, an equation can be written (Knauss), as follows,

$$L = I (10^{-5/2} I + 1) ^{2/3} 10^{-3} \text{ sones}$$

where I represents intensity in units of 10^{-16} watt per square centimeter. The difference between the values given by this equation and the function in Fig 43 reaches 50 per cent at 10 and 120 db, but between these values the difference is less. Still, for accurate computations, it is probably better to rely on a table or a graph of the loudness function rather than to use an equation.

The curve for 1000 cycles in Fig 43 is quite accurate for all tones between about 700 and 4000 cycles. At other frequencies, loudness is a somewhat different function of intensity, as shown by the other curves of Fig 43. These curves were determined by equating the respective tones to the 1000 cycle tone in loudness (see below), and then assigning loudness-values on the basis of these loudness equations. It should be possible, of course, to carry out the fractionation procedure for each frequency in turn and obtain curves identical to those of Fig 43. For the few cases in which data are available, reasonable agreement can be demonstrated. In general, the lower the frequency the more rapidly does loudness grow as a function of intensity, at least for

intensities below the 100-db level. Thus a tenfold (20-db) increase in the intensity of tones whose loudness is 0.1 sone produces, in a 50-cycle tone, a two-hundredfold increase in loudness, but only an elevenfold increase in a 1000-cycle tone. At intensities above 100 db, however, all frequencies below approximately 50 cycles increase less rapidly than the 1000-cycle tone.

The curve for 10 cycles was obtained from an experiment by Bekésy (22), in which he equated a 5-cycle and a 10-cycle tone to a 50-cycle tone in loudness (see Fig. 46). Bekésy reports that the loudness of these very low tones increases to a maximum and then declines at higher intensities. The threshold of feeling is reached before the maximum is attained, but apparently Bekésy's observers were able to make loudness judgments at intensities above the threshold of feeling.

The curves of Fig. 43 contain important implications for the problem of the reproduction of music by electrical devices. The original quality of a selection can be maintained by a system which reproduces all frequencies equally effectively only when the intensity level of the reproduction is the same as the intensity level of the original. Thus, at the proper intensity, a radio transmitter and receiver of perfectly uniform frequency response may reproduce a musical rendition whose component frequencies are all of the same *loudness* for the listener as they would be in the broadcasting studio, but at weaker intensities the selection would appear to have lost its low frequency tones. Hence, efforts to conserve the relative loudness of the low frequencies are ineffective unless account is taken of the intensity level at which the reproduction is to be made.

OTHER METHODS OF ESTIMATING LOUDNESS

The loudness-scale in Fig. 43 was constructed from data obtained by the method of *fractionation and its variations*. Can this loudness scale be verified by other methods, such as the method of *bisection* and the method of *equi-distances*? Such verification is theoretically possible—in fact, it is theoretically required if the loudness-scale is valid. The ability of any two methods to confirm each other is conditioned, among other

things, upon our ability to eliminate constant errors in the experimental procedures

The Method of Bisection Under this method the observer is required to set a variable tone until it is midway between two fixed tones in loudness. Objection has been made by Gage (1) to this method on grounds of internal inconsistency. His observers first bisected a loudness-interval to obtain the halfway point. Then they bisected the upper half to obtain the three-quarter point and the lower half to obtain the one-quarter and finally they bisected the distance between the one-quarter and the three-quarter points to yield a second halfway point. This second halfway point should be identical with the first half way point. Instead, it was consistently higher (louder) than the original bisection.

A repetition of this experiment, under slightly different conditions (Newman, Volkmann, and Stevens), gave results which, unlike Gage's, showed internal consistency. These results confirm the demonstration by Wolff that consistency is possible, and suggest that, when there is a lack of consistency in the results of bisection, we should look for constant errors in the procedure. Clearly, if in the method used by Gage there had been a slight positive error in *each* bisection, the cumulative effect would be large enough to account for the discrepancy observed.

When the results of experiments on bisection are compared with our expectations based on the loudness-scale, the situation becomes equivocal. Most of the bisections of short intervals disclose excellent agreement, but bisections of long intervals fail disconcertingly. In the case of these long intervals we are faced with the paradox that, when an observer sets a tone to a loudness one half that of a given tone, he does not do the same thing as when he sets a tone to a loudness halfway between that of the same given tone and a tone whose loudness approaches zero (Wolff). The bisection always gives a value lower than the fractionation, when a long interval is involved. One of Gage's observers, for example, *bisected* the interval from 0.1 to 6.0 sones and obtained the value of 0.8 sone. Setting a

tone to *half* the loudness of 60 sones would, of course, result in a loudness of 30 sones. What could account for this discrepancy of almost fourfold?

A possibility is that the observer assumes two very different attitudes under the two conditions. Preliminary experiments (Stevens and Volkman) have demonstrated that, in approaching the problem of bisecting a loudness interval, one can aim either at setting the middle tone halfway between the other two or at an adjustment such that the ratio of the middle tone to the lowest tone equals the ratio of the highest tone to the middle tone. In other words, one can aim either at the arithmetic or at the geometric mean. Different results are obtained by observers having these two attitudes. Thus a bisection of the interval from 5 to 20 sones would yield 12.5 sones under the first attitude and 10 sones under the second. The inability of observers to keep separate these two attitudes might possibly account for both the direction and the magnitude of the discrepancies in the experimental results.

The Method of Equi Distances. This method is similar to that of bisection, except that the two intervals to be equated do not have a point in common. An interval in one part of the loudness scale is set to equal an interval in another part. The intervals may or may not overlap.

Here again we are confronted with the possible source of error that the observer may set the tones to show what he deems to be either equal distances or equal ratios. When the intervals are small and fairly close together, however, these two attitudes may lead to indistinguishable results.

Wolff used this method to equate several intervals to three different standard intervals whose magnitude was very nearly 7 sones in each case. In all but two of the fifteen cases reported the adjustments were to within 1 sone of the size of the standard intervals. Hence, it appears that in these cases the observers aimed consistently at equal subjective distances, and their ability to obtain the results predicted by the loudness-function (Fig. 43) offers interesting confirmation of the loudness scale erected on the basis of fractionations. The results are not what

we should predict on the assumption that these observers were setting the tones to produce equal ratios

EQUAL LOUDNESS CONTOURS

The preceding treatment of problems relating to a loudness scale has regarded loudness as a function of intensity. With frequency held constant—usually at 1000 cycles—we have seen how loudness varies when intensity is altered. As already indicated in Fig 43, however, loudness also varies with frequency, when intensity is held constant. The precise relation between loudness and frequency can be discovered by mapping what are called equal loudness contours, that is to say, by determining at what intensities tones of different frequencies appear equal in loudness to a standard tone (1000 cycles) at various intensities.

Fletcher and Munson (1) equated tones in an earphone to a

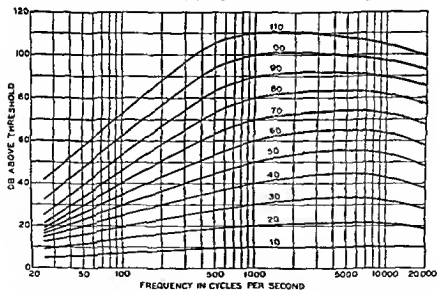


FIG 44 Equal loudness contours plotted against sensation level (ordinate). All of the tones lying on each contour sound equal in loudness. The number (parameter) attached to a curve gives its loudness-level (Fletcher and Munson, 1)

standard frequency of 1000 cycles—the accepted standard for loudness-comparisons—and obtained the results shown in

Fig 44 Here the contours are plotted against an ordinate representing sensation level (decibels above the average threshold of the observers used in the experiment) The loudness-level in phons is indicated by the number on each contour, and is determined by the intensity of the 1000-cycle tone lying on the contour. Thus all tones on the contour marked 50 sound equal in loudness to a 1000-cycle tone 50 db above threshold These curves in Fig 44 represent the best set of smooth curves the experimenters could draw through the observed points

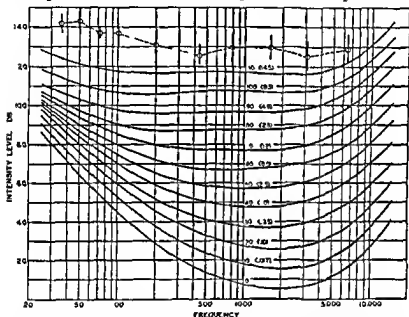


FIG 45 Equal loudness contours plotted against intensity (decibels above reference pressure) The zero contour is the curve for minimum audible pressure The dotted curve at the top represents Wegel's data for the threshold of feeling The parameter is designated as loudness level (first number) and as loudness in sones (number in parentheses)

Now, often it is desirable to know the course of the equal loudness contours as a function of the sound pressure at the eardrum of the listener Thus, by plotting the functions of Fig 44 against an ordinate representing pressure level (decibels above 0.0002 dyne per square centimeter), we obtain the curves of Fig 45 The lowest contour (zero) is the same as the thresh

old curve for minimum audible pressure, shown in Fig 17 (p 50), the upper curve (dotted) represents the threshold of feeling, as shown in Fig 19 (p 59). The contours in Fig 45 are numbered in two ways. The first number indicates the level, in decibels, or phons, of the 1000-cycle tone above threshold, and the second number (in parentheses) indicates the loudness, in sones, of the tones represented by each contour. In other words, the first number represents *loudness level* and the second number *loudness*. The threshold of feeling corresponds approximately to the loudness-level of 120, or to a loudness of 240 sones.

Instead of plotting the equal loudness contours using the threshold for minimum audible pressure as the reference contour, as in Fig 45, we could plot them on a similar grid using as the threshold function the curve for the minimum audible field, curve 2 in Fig 17. We should then obtain what have been proposed as the standard loudness-contours of pure tones under open field conditions. But these contours are suspect. The equal loudness relations (Fig 44) were determined, not in an open sound field under standard conditions of listening, but with a telephone receiver on the ear. Recent measurements (Churcher and King) have disclosed a slight discrepancy between equal loudness contours obtained in a free field and those in Fig 44. Consequently, an extensive redetermination of loudness-relations, when the observer listens to a plane sound wave in a free field, will have to be made before we can adopt a set of standard contours representing loudness relations under the standard condition of listening.

Another manner of plotting the relation between the three variables—frequency, intensity level, and loudness level—for the experiment in which sound intensity is measured directly at the place where the head of the observer is to be (field intensity) is shown in Fig 46. Here loudness level is plotted as a function of intensity level, with frequency as the parameter. (These curves will need revision when more field measurements are available.) The curves for 5 and 10 cycles were not taken from the work of Fletcher and Munson, as were the other

curves, but from an experiment reported by Békésy (22), in which the 5 and 10-cycle tones were each equated to a 50-cycle tone in loudness. The dotted portion of these two curves represents the behavior of loudness-level at intensities above the threshold of feeling. Clearly, these curves pass through a maximum. The curve for 30 cycles suggests that, if continued, it would likewise reach a limiting value and perhaps decline. These curves in Fig. 46 were used to determine the loudness functions for the lower frequencies, as shown in Fig. 43.

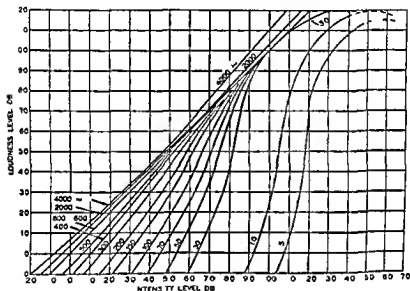


FIG. 46 Showing how loudness level varies with intensity level at different frequencies (parameters). (After Fletcher and Munson 1 and Békésy 22.)

In an effort to ascertain the reliability with which observers can judge the relative loudness of tones of different frequency, Steinberg and Munson worked out the distributions of loudness judgments for a large group of people with normal hearing. By the method of constant stimuli, two different tones, 100 and 5000 cycles, were equated in loudness to a 1000-cycle standard. Under these conditions, 97 people equated 5000 and 1000 cycles in loudness with a probable error of 5.2 db, and 98 people equated 100 and 1000 cycles with a probable error of 6.4 db.

With the same groups of observers (all of them inexperienced in auditory judgments) the threshold intensity of the 1000-cycle tone was determined by a similar procedure and the probable error of the distribution of threshold values was 3.6 db

In order to account, if possible, for the rather wide distribution of loudness-judgments among these observers, several factors have been investigated with the following results

- 1 The effect of experience is unimportant Experienced observers differ from each other as much in judgments of loudness as do inexperienced observers

- 2 Variations in the judgments of a single observer at different times cannot account for all the scatter among the group The deviations of repeated tests by a single observer tend to be smaller, by about one half, than the deviations of a number of observers making one test each

- 3 For these people, whose hearing is essentially normal, the loudness-judgment is apparently not greatly dependent upon the acuity of hearing

- 4 Differences in the *effective* intensity of the stimulating tones after they have reached the organ of Corti probably account for only a small part of the deviations

All these factors together probably account for some, but certainly not for all, of the scatter among the loudness judgments of normal listeners The judgment itself, like all psychological judgments appears to be inherently variable

RELATION BETWEEN LOUDNESS AND MASKING

There is an interesting and important relation between the loudness of a sound and its ability to mask other sounds (Fletcher and Munson, 2) Masking is defined as the change in the threshold of one tone due to the presence of another, the masking tone This change is measured in decibels (see Chapter 8) Now, the fact that the threshold of a tone is raised by the presence of a masking sound may be taken to indicate that some of the receptors on the basilar membrane are already excited by the masking sound The amount that the tonal threshold needs to be raised in order to override the effects of

the masking sound may be regarded as a measure of the extent of nervous activity created by the masking sound. The amount of this masking may be considered, furthermore, to represent the contribution to loudness arising from that region of the basilar membrane which corresponds to the frequency of the masked tone. In other words, when we consider a small unit of extent on the basilar membrane, masking, excitation, and loudness are functions of one another. Then, if these elementary assumptions are valid, it follows that the area under a masking audiogram should be a definite function of the total loudness of the masking sound.

We can express these relations mathematically as follows

$$dL = F(M)dx$$

where dL is an element of loudness, $F(M)$ is a function of the masking and is the loudness per unit length, and dx is an element of length on the basilar membrane (this element is taken as 1 per cent of the length of the membrane).

Then, if we assume that each unit of length of membrane contributes equally to the total loudness when the excitation of all units is equal (as measured by masking), we can integrate,

$$L = \int F(M) dx$$

Now, if we could obtain a sound which would give a masking audiogram having a constant value over a certain range of frequencies and zero value for all other frequencies, we could determine its loudness and its extent on the basilar membrane (from the curve in Fig. 35, p. 96), and thereby solve the equation above for the value of $F(M)$. But no such sound can be obtained. The frequencies in an acoustic spectrum can be confined to a definite band, but the masking will always trail off gradually, especially above the frequency band.

In order to circumvent this difficulty, Fletcher and Munson used a wide band of thermal noise having a continuous spectrum and capable of stimulating practically the entire length of the

basilar membrane. The intensity-profile of this sound-spectrum was adjusted so as to mask equally tones of all frequencies. Then, by measuring both the subjective loudness and the masking produced by this noise, the authors were able to compute the function, $F(M)$, and obtain the curve shown in Fig. 47.

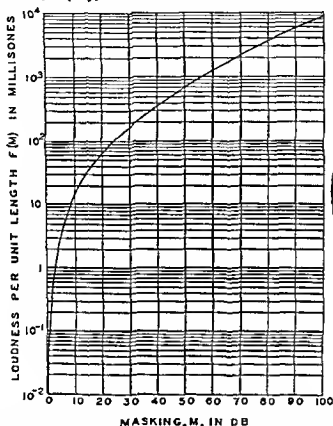


FIG 47. Loudness as a function of masking. The ordinate gives the loudness, $F(M)$, contributed by a small unit of length (1 per cent or 0.3 mm) of the basilar membrane when it is excited to such an extent that it would produce a masking equal to the value M . Example: when a portion of the basilar membrane is excited by a sound which would raise the threshold of another sound, stimulating the same region, by 57 db, each unit (1 per cent) of the membrane in that region contributes a loudness of 10^3 millisonnes to the total loudness of the sensation. (After Fletcher and Munson, 2)

This curve gives the loudness, in millisonnes (1 millisonne = 0.001 sone), resulting from uniform excitation of 1 per cent of the basilar membrane. (It must be remembered that *excitation* is

here defined as masking. Its relation to physiological processes in the ear has not been fully determined.)

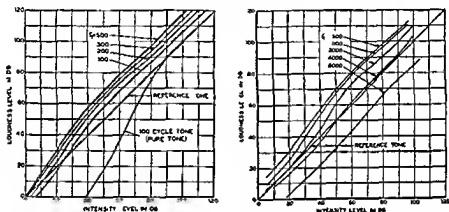
Knowing the curve of Fig 47, one can proceed to calculate the loudness of a noise. First, the masking audiogram of the noise is found by experiment. This audiogram is the curve representing the threshold of all audible frequencies when measured in the presence of the masking sound. Next, the loudness-values $F(M)$ are read from Fig 47 and are plotted against a scale representing the linear extent of the basilar membrane. Finally, a graphical integration of the area under the resulting curve gives a value proportional to the loudness of the noise in millisones. Fletcher and Munson (2) have developed special charts to facilitate these computations.

THE LOUDNESS OF MULTI COMPONENT TONES

The methods already outlined are adequate for dealing with the loudness of single pure tones and of sounds having a relatively continuous spectrum, such as thermal noises. Efforts to calculate the loudness of tones composed of a limited number of separate frequencies have met with only meager success. The case is simple enough when components are added which are sufficiently separated in frequency as not to stimulate overlapping areas on the basilar membrane, for then the loudnesses of the tones add in a simple arithmetic manner. But when there is overlap, and one tone begins to mask the other, complications arise, and the loudnesses are not simply additive. The resulting effects must, in general, be determined by experiment.

A particularly interesting example is that in which all the component tones are in harmonic relation. The sets of curves in Figs 48 and 49 represent the relation between loudness-level and intensity level for tones having such a structure (Fletcher, 3). Each complex tone had ten harmonic components all equally intense. The numbers attached to each curve give the fundamental frequency of vibration. In Fig 48 the curve for the 100-cycle pure tone is included for comparative purposes. It is seen that changing the overtone structure from no over-

tones to nine equally intense ones has increased the loudness-level from 20 db to 60 db for the particular tone having a fundamental frequency of 100 cycles and an intensity level of 51 db. As seen in Fig 43, this corresponds to a change in loudness from 0.1 to 6.0 sones, or an increase of sixtyfold. Increases in loudness are produced on all tones by such a change in overtone structure, but the increases are not so great for the higher frequencies, or for the higher intensities. It will be seen



FIGS 48 AND 49 The loudness level achieved by adding together 10 harmonic frequencies each at an intensity level as shown by the abscissa. The fundamental frequency f_1 is indicated for each curve. (Fletcher 3)

that, of the ten-component tones, those having a fundamental frequency between 400 and 800 cycles are the loudest. These quantitative results show why it is easy to increase the loudness of a musical tone by increasing its overtone content, a practice which is common in producing musical tones. Practically all the loudness of the tones from the piano strings of low pitch is due to the higher overtones.

RELATION OF LOUDNESS TO THE THRESHOLD OF HEARING

It can be seen from Fig 44 that when a person's threshold is normal, the equal loudness contours bear a definite empirical relation to the threshold of hearing. Is this relation the same for the ear whose threshold, at certain frequencies, is abnormal?

The answer to this question reveals interesting aspects of the mechanism of the perception of loudness

In general, if the threshold of hearing at a given frequency is above normal, the perception of loudness at high intensities may or may not be normal. Thus, in a series of tests (Steinberg and Gardner) several people having some degree of unilateral deafness, i.e., one impaired and one normal ear, were required to make a tone heard with the deafened ear equal, in loudness, to a tone heard with the normal ear. For some people, the impaired ear heard less well than the normal ear for all sound levels. For others, tones which were well above the threshold of the deafened ear were heard about equally well with either ear. In other words, such deafened ears tended to hear loud sounds with almost normal loudness. People with this type of deafness are the ones who seem to hear as well as normal people when they are in noisy surroundings. The reason is obvious. There is also an intermediate case where hearing is improved with intensity, but does not become fully normal.

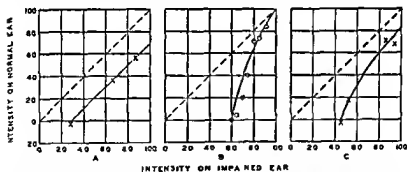


FIG. 50 The intensities of two tones, one in a normal ear and one in a deafened ear, which produce equal loudness. Three general types of deafness are indicated by these curves. (After Steinberg and Gardner)

Figure 50 illustrates these three types of ears. Each plot represents the intensity level at which a 2000-cycle tone in the normal ear sounded as loud as a 2000-cycle tone in the impaired ear. If both ears were normal, the observed points would, in each example, lie along the dotted line. Plot A shows the type

of deafness in which the increase in intensity needed to reach threshold is the same as that necessary to yield equal loudness at higher intensities. In plot *B*, however, although the threshold of the impaired ear is elevated 60 db above the threshold of the normal ear, equality of loudness is achieved when the intensity level in both ears is 100 db. Hence, in this impaired ear, loudness grows much faster as a function of intensity than it does in normal ears. Plot *C* represents an intermediate type of hearing loss: hearing improves at high intensities but does not reach normal. The solid curve in each plot represents the relation of loudness in the two ears as calculated by an empirical method (see below).

We can account for the curve of plot *A* if we assume that all frequencies entering the ear were attenuated approximately 30 db before they became effective for sensation. This type of deafness is common to defects in the middle ear. The curve of plot *B*, however, cannot be explained without considering the nature of loudness. Referring to Fig 43, let us assume that there is a loss of 6 sones in the loudness of the tone. Such a loss might result from a deficiency in the total number of neural elements which normally contribute to give a tone loudness—a case of ‘nerve-deafness,’ so called. Subtracting 6 sones from the loudness function at all intensity levels, we obtain curve *B* in Fig 51. Curve *A* is the normal loudness function. Clearly, at high intensities an ear, having an assumed loss of 6 sones, tends to hear with practically normal loudness, although below 60 db the ear is deaf and hears no loudness at all. This picture agrees precisely with that presented in plot *B* of Fig 50. Hence, it appears that the variable type of deafness—where hearing becomes normal at high intensities—is associated with a condition which results in a fixed reduction in loudness, as contrasted with a fixed reduction in effective intensity for the other type of deafness.

If, as seems probable, the variable type of deafness occurs when there is a deficiency of neural elements, the hearing loss caused by a masking sound would be expected to be of the variable type. The nerve fibers which are activated by the

masking sound are ineffective in contributing to the loudness of another tone heard in the presence of the masking sound. In other words, masking is an effective means of decreasing the

available supply of neural elements and of producing the equivalent of a variable deafness.

These conclusions were borne out under experimental test. The observer adjusted a tone heard in his one unmasked ear until it sounded as loud as a tone of the same frequency heard in his other ear, which was being masked by a thermal noise. For tones of all frequencies from 250 to 8000 cycles, the threshold in the masked ear was raised by about 40 db, but at high intensities the loudness in the masked ear was approximately equal to the loudness in the unmasked ear. In other

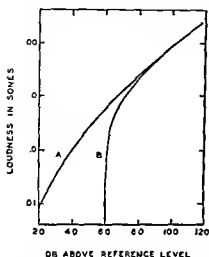


FIG 51 Showing how a defect which produces a fixed loss in loudness (6 sones) affects the loudness-function. Curve A represents the normal function, curve B a loss of 6 sones. The variable type of hearing loss presumably causes a fixed loss of loudness as measured in sones.

words, the results resembled those shown in plot B of Fig 50 and showed that the hearing loss due to masking is of the variable type.

The Calculation of Hearing Loss We have already noted the relation between the masking effects and the loudness of a sound for normal ears. If, from the masking audiogram of a sound its loudness to a normal ear can be calculated, the loudness heard by an ear having a variable type of deafness should be susceptible to the same methods of attack. For the normal ear, the area under the masking audiogram (plotted against the proper coordinates) is proportional to the loudness of the masking sound. For the ear having variable deafness, the area under the hearing loss audiogram is proportional to the

loss in loudness attributable to the deafness. This loss in loudness can be computed by the method that is used to compute the loudness of a masking sound.

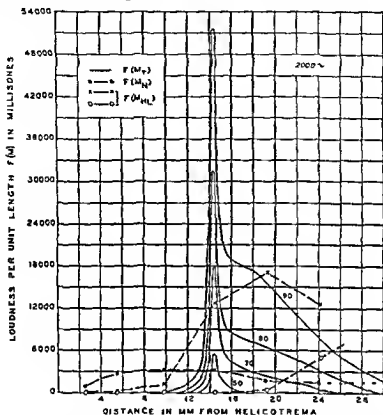


FIG 52 The loudness-patterns, $F(M_T)$, produced on the basilar membrane by a 2000-cycle tone at the various sensation levels indicated by the numbers attached to the curves. Each curve relates the loudness per unit length (1 per cent, or 0.3 mm) of the basilar membrane to the position of the excitation on the membrane, and the area under each curve is proportional to the loudness of the tone. By means of the function in Fig 47, this loudness per unit length was obtained from the masking audiogram of the tone. The masking audiogram of a thermal noise was used to calculate its loudness-pattern, $F(M_H)$, and the hearing loss audiograms of two ears were converted into loudness loss patterns, $F(M_{HL})$. In the presence of the thermal noise, or of the hearing losses, the loudness of the 2000-cycle tone is given by the area between the solid and the appropriate broken curve. (After Steinberg and Gardner)

Figure 52 illustrates this method. The solid curves represent the loudness-patterns for a 2000-cycle tone at various sensa-

tion levels. These curves are the masking audiograms of the 2000-cycle tone after they have been transformed into functions expressing loudness per unit of length (0.3 mm) of the basilar membrane. This transformation was made with the aid of the function $F(M)$ in Fig 47 and a function like that in Fig 35 (p 96). The solid black points represent the loudness-pattern obtained, in a similar way, from the masking audiogram of a thermal noise, and the circles and crosses give the pattern of loudness loss for the two ears of a deafened person. Now, by simply measuring the areas under the parts of the normal loudness-patterns which rise above the patterns of loudness-loss, we obtain the loudness, as heard by the affected ears. Likewise, the area enclosed between the normal loudness pattern and the masking pattern gives the net loudness of the 2000-cycle tone when heard in the presence of the masking noise.

It was by this method that the solid curves of Fig 50 were determined. The agreement between the calculated and the observed loudness is rather satisfactory. In order to obtain the curve in plot C of Fig 50, it was, of course, necessary first to subtract from the measured hearing loss the amount not due to the variable type of deafness.

DIFFERENTIAL SENSITIVITY TO INTENSITY

The smallest detectable change in the intensity of a tone determines the intensive differential sensitivity of the ear. This sensitivity may be strictly defined as the reciprocal of the just noticeable change, or DL (difference limen). Interest in the measurement of DL's dates from the time of E. H. Weber, who proposed the rule that the ratio of the DL to the intensity at which it is determined (the Weber fraction) is constant for any sense department. This ratio is also called the *relative difference limen*, and we know now that Weber was mistaken about its constancy. Early efforts to measure auditory sensitivity suffered from technical difficulties which necessarily condemned them to incompleteness. Knudsen (1) reviewed the early work and set about to explore the DL over a wide range of intensity. His work was later superseded by a still more

thorough set of measurements by Riesz (1). It is these measurements which we shall examine in detail.

Riesz presented his tones monaurally by means of a special moving-coil receiver designed to be especially free of distortion. The receiver was connected to the outputs of two oscillators in such a way that both oscillators activated the receiver simultaneously and produced beats when the frequencies of the two impressed tones were close together. First the tone from one oscillator was presented at a definite sensation-level and then the intensity of the tone from the other oscillator was increased, from a point near zero, until the observer was just able to detect a beat. From the intensities of sound needed to obtain this beat, the intensity at the maximum and at the minimum of the beat

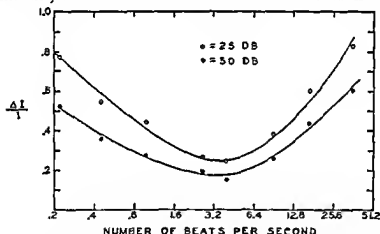


FIG. 53. The dependence of the relative difference-limen ($\Delta I/I$) upon the rate of variation in the intensity of a tone. The curves are for the sensation-levels of 25 and 50 db. (After Riesz, 1.)

could be calculated. The difference between the maximum and the minimum was taken as defining the DL.

Although the type of transition from minimum to maximum intensity by the method of beats has not usually been employed in measurements of differential sensitivity, it possesses the advantage that it produces a simple fluctuation in intensity which is not complicated by the possible presence of an undetermined number of transients. If the transitions from the weaker to the louder tone are made abruptly, some of the energy will

be scattered to frequencies higher and lower than the impressed frequency. These transients may be audible, and provide the observer with a false clue.

The size of the DL was found to be a function of the rate of the fluctuations in intensity. A representative curve showing the size of the relative DL as a function of the rate at which the beats were presented is given in Fig. 53. It is characterized

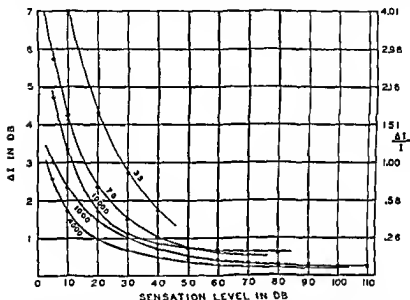


FIG 54 The relation between the difference limen (ΔI) and sensation level, at various frequencies (parameters). The relative difference limen is shown on the scale at the right. The size of ΔI in decibels is equal to $10 \log (1 + \Delta I/I)$. (Data from Riesz, 1)

by a broad minimum in the neighborhood of 3 cycles, and this rate was adopted for the experimental determination of the DL for intensity.

Average curves giving the size of the relative DL as a function of intensity (sensation-level), with frequency as the parameter, are shown in Fig. 54. At a given frequency the relative difference-limen approaches a constant value for intensities above 50 db, but increases rapidly as the intensity is reduced

toward the auditory threshold (See Table II for tabulated data)

Figure 55 shows the behavior of the relative DL as a function

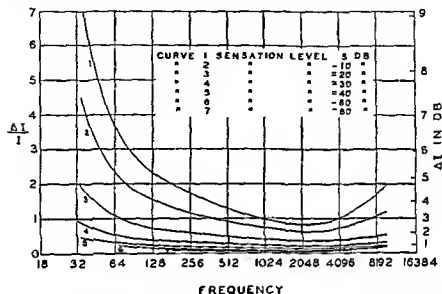


FIG 55 The relation between the DL and frequency, at various sensation levels (After Riesz 1)

of frequency for different values of the parameter intensity. The relative DL is a minimum at a frequency of about 2500 cycles, although the minimum is less sharply pronounced at high intensities than at low. The region of the greatest differential sensitivity of the ear corresponds to the frequency range of greatest absolute sensitivity.

TABLE II

Differential sensitivity to intensity at various frequencies and sensation levels. Two entries appear at each frequency and sensation level. The upper entry gives the value of $\Delta I/I$ (in terms of energy) and the lower value (italicized) gives the value of ΔI in decibels. These data were obtained from 12 observers at the Bell Telephone Laboratories. (Printed by permission.)

Sensation level	5	10	20	30	40	50	60	70	80	90	100	110
Frequency												
35	7.55 <i>3.32</i>	4.30 <i>2.24</i>	1.70 <i>1.31</i>	.87 <i>.72</i>	.50 <i>.76</i>							
70	2.75 <i>1.74</i>	1.64 <i>1.22</i>	.73 <i>.38</i>	.42 <i>1.32</i>	.27 <i>1.04</i>	.19 <i>.73</i>	.15 <i>.61</i>	.14 <i>.37</i>				
200	1.91 <i>1.71</i>	1.21 <i>1.44</i>	.56 <i>1.33</i>	.33 <i>1.24</i>	.22 <i>.84</i>	.17 <i>.38</i>	.13 <i>.33</i>	.11 <i>.41</i>	.10 <i>.41</i>	.10 <i>.41</i>		
1 000	1.01 <i>1.03</i>	.72 <i>2.31</i>	.40 <i>1.48</i>	.26 <i>1.00</i>	.18 <i>.71</i>	.13 <i>.33</i>	.10 <i>.41</i>	.08 <i>.33</i>	.07 <i>.29</i>	.07 <i>.29</i>	.06 <i>.27</i>	.06 <i>.27</i>
4 000	.77 <i>1.48</i>	.43 <i>1.70</i>	.25 <i>.97</i>	.17 <i>.68</i>	.12 <i>.49</i>	.10 <i>.41</i>	.07 <i>.29</i>	.06 <i>.27</i>	.06 <i>.27</i>	.05 <i>.27</i>	.05 <i>.27</i>	
7 000	1.54 <i>1.03</i>	.92 <i>2.83</i>	.41 <i>1.49</i>	.23 <i>.50</i>	.17 <i>.48</i>	.15 <i>.41</i>	.13 <i>.33</i>	.12 <i>.49</i>	.11 <i>.41</i>	.10 <i>.41</i>		
10 000	2.00 <i>1.72</i>	1.16 <i>3.34</i>	.43 <i>1.70</i>	.29 <i>1.19</i>	.22 <i>.86</i>	.19 <i>.71</i>	.17 <i>.48</i>	.15 <i>.31</i>	.14 <i>.37</i>			

SPECTRAL ANALYSIS OF THE STIMULUS

It is of interest, at this point, to inquire into the nature of the stimulus used by Riesz for obtaining his DL's, and to compare it with the stimulus used to measure the DL's for frequency. The stimulus for discrimination of frequency was obtained by modulating the frequency of a tone, and, as outlined in the preceding chapter, it consisted of a group of five or more steady components which, by beating with each other, set up a migrating disturbance on the basilar membrane. The spectrum of Riesz's stimulus was, of course, much simpler, for it consisted of only two steady components, a large and a small, spaced 3 cycles apart. How are we to regard the action of these components?

Each component sets up on the basilar membrane a disturbance whose maximal amplitude may be represented schemati-

cally by the solid curves of Fig 56. The two components differ in frequency, and, consequently, the two overlapping disturbances on the membrane are alternately in and out of phase with each other. When in phase, they reinforce to produce a net disturbance corresponding to the dotted curve whose maximum is at point *A*. When out of phase, point *B* represents their maximum. Clearly, as the maximum moves from *A* to *B*, not only is there an increase in the total disturbance, but the maximum moves laterally along the membrane by a slight amount. Apparently this lateral displacement is too small to produce a noticeable difference in pitch, although conceivably it could do so.



FIG 56 Showing how the pattern of disturbance on the basilar membrane changes when a faint tone beats with a loud tone. Two dotted curves show the extreme positions of the disturbance due to the alternate reinforcement and cancellation of the two solid curves.

Incidentally, the lateral excursion of the disturbance could be prevented by introducing another side band on the other side of the large component. With the two side bands of the same amplitude and the proper phase, the line from *A* to *B* could be made exactly vertical, and we should have a case of pure amplitude modulation (see Chapter 9). It is doubtful, however, that the results of a pure amplitude modulation would be different from those reported by Riesz.

FACTORS INFLUENCING DIFFERENTIAL SENSITIVITY

Although we must accept the results of Riesz as the most comprehensive and satisfactory measurement of differential sensitivity available at present, it is clear, from the lack of agreement among previous investigators, that the values obtained depend to a large extent upon experimental conditions. We shall consider some of these factors.

Monaural versus Binaural Observation Earlier results did

not disclose the fact, but the claim has recently been made, that in binaural listening it is possible to detect a change in intensity 15 to 30 per cent smaller (on a decibel scale) than that which is perceptible in monaural listening (Churcher, King, and Davies, Upton and Holway). Whether or not so large a difference would have appeared in Riesz's results had he used binaural instead of monaural listening is problematic, but the evidence supports the notion that auditory discrimination of intensity is finer when both ears are involved.

Duration of the Tones In both monaural and binaural listening the DL is smaller when the duration of the tones is greater. Upton and Holway showed that the decrease in the size of the DL is related to the exposure time of a tone according to an exponential function.

Transition between Tones For optimal conditions the transition between the tones to be compared should be abrupt, instantaneous, and silent. A gradual transition, such as the sinusoidal variation used by Riesz, is less easy to detect than an abrupt transition, but, as already suggested, an abrupt transition may involve the production of unwanted transients.

Any interval of silence between the tones decreases the sensitivity of the ear to a change of intensity. The introduction of an interval of half a second, under certain conditions, increases the required intensity change by a third (Montgomery). Under other conditions, going from a one third second to a three second interval increases the required change twofold.

The effect of transition time can be strikingly demonstrated (Rawdon-Smith and Grindley) by presenting an observer with a tone which is increased very slowly in intensity and then decreased suddenly to the original value. When this process is repeated, the observer reports hearing a tone which, by discrete jumps, grows less and less loud. Objectively, of course, the intensity is the same at the end of each jump.

Control of Presentation Where two discrete tones are being presented for comparison, it is important that the observer be able to control the exact instant of transition from one tone to the other. Thus, Montgomery found that the required

intensity-change was reduced by one-half when the observer was allowed to operate the switch himself. This seemed to be due to the fact that, under these conditions, the observer could be prepared for the change at the exact instant it occurred. A somewhat better judgment is also obtained when the observer is permitted to listen to the tones as many times as he desires before making his decision as to which is louder.

An illustration of the influence of some of the factors affecting differential sensitivity is given in Table III.

All the values in this table were obtained from the same observer listening monaurally to a thermal noise at 40 db above threshold. Similar results were obtained using a 1000-cycle tone.

TABLE III

Condition	Decibels	$\Delta I/I$
1 Switch not controlled by subject, one comparison, half second interval between tones	0.8	0.20
2 Same, except no interval between tones	0.6	0.15
3 Repeated comparisons, no interval between tones	0.4	0.096
4 Switch controlled by subject, repeated comparisons, no interval between tones	0.2	0.047
5 Sinusoidal variation (continuous presentation) (cf. Riesz)	0.5	0.12

NATURE OF THE DIFFERENCE LIMEN

Under conditions designed to measure the DL, the observer's response is always variable. This phenomenon of fluctuation, familiar to everyone who has made psychophysical measurements, necessitates the adoption of some statistical criterion for determining the value of the DL. The value usually selected is the difference which the observer is able to detect 50 per cent of the time. Smaller values would be detected less and larger values more than 50 per cent of the time.

In order to illustrate how the instantaneous sensitivity of the ear varies from time to time, Montgomery has defined a quantity S which is variable with time in such a way that at any

instant the ear is able to perceive any increment of intensity greater than S , but is not able to perceive an increment less than S . In his experimental work, a definite value of the increment was chosen, and the proportion of the time that the

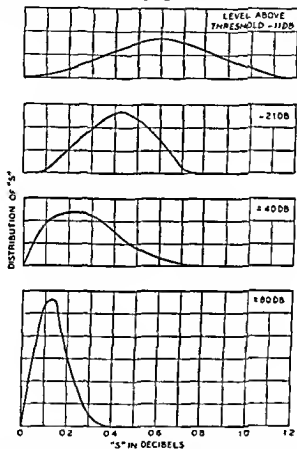


FIG. 57. Showing how the sensitivity of an observer varies with time. The quantity S is a measure of the instantaneous sensitivity of the ear, and is determined by the value of the increment which, at any instant, would be just detectable. The area under a curve, between any two limits, is proportional to the probability that S will be between those limits at any instant. Each curve is for a different sensation level, as indicated (Montgomery)

observer could detect this increment was taken as defining the proportion of the time that S had a value less than the increment. With this interpretation we may regard the curves

of Fig 57 as the distribution curves of S . Then, the portion of the area under one of these curves, between any two limits, is the probability that S will be between those limits at any instant. Actually, these curves were derived from the slopes of the psychometric functions obtained from the experiment. (See Guilford for a discussion of these functions.) The curves of Fig 57 enable one to appreciate readily the manner in which the sensitivity of the ear varies with time.

The curves of Fig 57 show a distribution of sensitivity such as is usually found in a psychophysical experiment. These curves exhibit a resemblance to the 'normal curve' for the distribution of chance errors, and it has usually been assumed that they are, in fact, the result of chance variation on the part of the observer. However, in order to obtain 'normal curves' under these conditions, we must assume, not only that sensitivity varies in random fashion with time, but also that some of this variation occurs *between* or *during* the presentation of the two tones. At least such an assumption is required if we are to conceive of differential sensitivity as being quantal in nature.

Let us examine the quantal notion more closely.

The simplest assumption to be made about discrimination is that the organism can detect an increment to a stimulus when, and only when, the increment is large enough to excite one additional 'neural unit' (nerve fiber?). Then, the size of the necessary increment will depend upon how far the previous stimulus has exceeded the threshold of the last excited unit. As depicted schematically in Fig 58, a noticeable difference will occur when an amount Δ is added to the stimulus, because then the next 'neural unit' NU will be excited.

Now, suppose the over all sensitivity of the organism is in random fluctuation. Or, what amounts to the same thing, suppose the height of the stimulus column in Fig 58 varies in chance fashion with time. Then, the size of the necessary increment Δ will vary from zero to the size of the interval NU . But, since one size of the necessary increment is as probable as any other, the probability that any given increment will be noticed is equal to the ratio of Δ to NU . This simple relation

will hold provided no change in sensitivity occurs *between or during* the presentation of the two stimuli to be compared. If

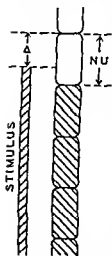


FIG 58 Schema illustrating the nature of differential sensitivity according to the assumption that it is a quantal phenomenon. Δ is the increment which must be added to the stimulus in order to excite an additional neural unit. The neural unit may or may not correspond to an anatomical unit, such as a single nerve cell. (After Békésy 6)

these conditions are fulfilled, the psychometric function should become a straight line, and the curves for the distribution of sensitivity, as shown in Fig 57, should become rectangular instead of bell shaped.

Can such results be realized in a concrete experiment?

Békésy (6) presented a tone lasting only 0.3 sec, followed immediately by a second tone of the same duration and of variable intensity. The observer reported whether or not he noticed a difference in loudness between the two tones. The tones were produced in earphones which were incorporated in a bridge circuit. The circuit was tuned in such a way as to suppress the noise arising from the operation of switching from one tone to the other. Under these conditions it was possible to obtain the results shown in Fig 59. Plot A represents the distribution of judgments obtained with observers less practiced or less sensitive. Apparently two additional neural units are needed to produce a noticeable difference. Even with sensitive observers, such a distribution can be obtained when the tones are very weak, or when some disturbing factor is introduced into the experiment. Plot B is of greater theoretical interest. It is the sort which Békésy obtained from well practiced

observers, under the most ideal conditions, and it agrees precisely with what we should expect on the basis of our assumption regarding the quantal nature of discrimination. Hence, if Békésy's results can be substantiated in future experiments, we shall have good reason to accept the notion that the mechanism

of discrimination is fundamentally quantal in nature, although this fact is normally obscured by a random fluctuation in the over all sensitivity of the organism

In both plots the distributions fail to be symmetrical about the point of objective equality of the two tones (zero on the abscissa) Békésy explains this as being due to the fact that the

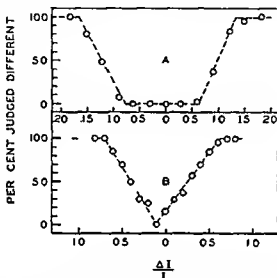


FIG 59 Showing the distribution of judgments regarding the sameness or difference of two tones which differ by an amount ΔI (After Békésy, 6)

first tone is of such short duration that it does not build up to the full loudness it would have if continued longer. Consequently, when the second tone follows at the same intensity, the observer experiences a growth in loudness, due merely to the factor of duration. This factor (or time-error) operates to shift all judgments in such a way that the tone judged equal 100 per cent of the time is a tone slightly less intense than the standard tone (See Boring, 3, for discussion of the time-error)

THE INTEGRATION OF DIFFERENCE LIMENS

From the data contained in Fig 54 it is possible to find the number of discriminable steps in loudness when proceeding from one intensity to another. A satisfactory method of determining this number is to plot the function $I/\Delta I$ (reciprocal

of the relative DL) against $\log I$ (or the decibel scale) and measure the area under the resulting curve. This area is proportional to the number of DL's between the limits bounding the area.

Figure 60 shows the result of an integration of the DL's for intensity (Riesz, 2). These curves show that the total number of discriminable steps between two sensation levels is different at different frequencies. Integrations taken all the way from the threshold of audition to the threshold of feeling, at various frequencies, show that the maximal number of steps occurs between 1000 and 2000 cycles (Riesz, 1).

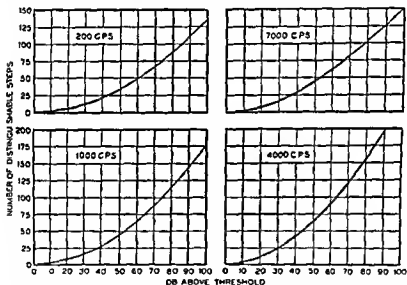


FIG. 60 Showing the relation between the number of DL's (ordinate) and the number of decibels (abscissa) that a tone is above threshold. These curves were obtained by integration of a function relating ΔI to intensity (Riesz, 2).

The Subjective Size of Difference Lamens for Intensity
 Now that we have a scale for the measurement of the subjective magnitude, loudness (Fig 43), it becomes possible to answer the question which has agitated psychologists since the days of Fechner regarding the subjective size of an intensive DL. Fechner assumed that all DL's are subjectively equal and

proceeded forthwith to integrate them in an effort to determine the magnitude of a sensation. However, it has been found that summing the same number of DL's for two tones of different frequency does not yield equal loudnesses (Newman). Work on equal sense-distances also failed to confirm Fechner's assumption, but suggested that the DL's at high intensities are subjectively larger than those at low intensities, although it could not be said how much larger (Titchener, 2). It should be noted that we are not here concerned with the constancy of the Weber fraction $\Delta I/I$, which was *another* of Fechner's assumptions, but only with the problem of subjective magnitude, i.e., the ability of an added just-noticeable difference to contribute always the same increment to the total subjective effect of the stimulus.

If Fechner's assumption regarding the subjective equality of DL's were correct, the summated DL's (Fig. 60) would yield a function proportional to the loudness-function of Fig. 43. These two functions are not proportional, but from their forms we can proceed to determine their relation, and thereby to measure the one in terms of the other. The relation turns out to be almost a power function, as is shown by the fact that straight lines are obtained in logarithmic coordinates when the one function is plotted against the other (see Fig. 61, and Stevens, 7). If the lines here are taken as defining the relation between loudness and the number of DL's above threshold, the equation

$$L = KN^2$$

can be written. Here L is loudness and N is the number of DL's above threshold. The constant K can be determined from the intercepts of the lines with the loudness-axis. The exponent is the same for all frequencies, because the slopes of the lines are the same. Of course, since the data for the higher frequencies could best be fitted by curves slightly concave downward, the exponent is not strictly constant, but the data probably do not warrant more precision in the determination of the exponent. On Fechner's assumption this exponent would be unity.

Now, to measure the size, in sones, of the first DL above threshold, we may set $N = 1$, and then the size becomes equal

to the value of K . The value of K varies with frequency, and is smallest for frequencies near 3000 cycles. Not only does the subjective magnitude of a DL depend upon the frequency of a tone, but it varies also as a function of the number of the DL above threshold. This relation is shown in Fig. 62. The equa-

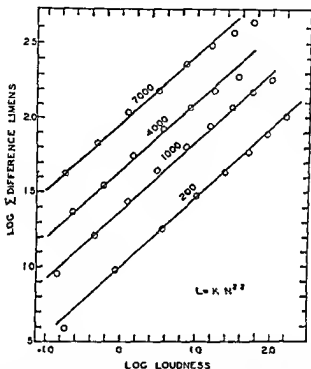


FIG 61. The relation of loudness (in sones) to number of DL's. The points for 7000 cycles have been shifted 0.5 logarithmic unit upward on the ordinate scale, in order to facilitate plotting. L represents loudness in sones, N the number of DL's above threshold, and K is a constant determined by the intercepts of the lines on the axis of log loudness at zero value of the ordinate. The values for K are .0070, .00112, .00028, .00070 for 200, 1000, 4000, and 7000 cycles respectively (Stevens, 7)

tion in this figure relates the size of a difference-limen DL to its number N , and was obtained by differentiating the previous equation. The vast disparity between the subjective magnitudes of different DL's is clearly apparent. Hence, their inte-

gration for the purpose of obtaining a numerical scale of loudnesses is not permissible

Before leaving the topic of the subjective size of the intensive DL, we should note the important implication for psychophysiology of the fact that the DL's are not equal. The

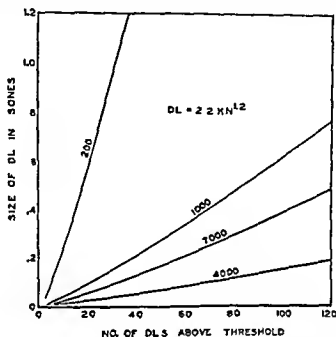


FIG. 62. The subjective magnitude of the DL's as a function of their number above threshold. K and N are the same as in Fig. 61. Frequency is the parameter. (Stevens 7)

hypothesis that a just noticeable difference occurs in a sensation when an additional 'neural element' is brought into activity is attractive for its simplicity. Equally attractive is the simple notion that loudness is proportional to the number of active 'neural elements' (see Chapter 16). The meaning of Figs. 61 and 62, however, is that these two notions are incompatible. If loudness is proportional to the number of active elements, a DL cannot be founded upon the addition of a single active element. Of course, it may be that neither of these relations between 'neural elements' and sensation is true—we do not know—but the ultimate solution of the psychophysiological problem of

loudness will have to account for the functions depicted in Fig 61 (cf Stevens and Davis)

THE TOTAL NUMBER OF DISTINGUISHABLE TONES

One more interesting question relating to difference limens deserves our attention. Once we know the values, throughout the audible range, of the DL's for frequency and for intensity, we can proceed to calculate the total number of pure tones that the ear can distinguish from one another. When we hold intensity at a medium value and vary frequency alone, there are about 1500 just noticeable steps from the lowest to the highest audible frequency. When we vary only the intensity of a tone in the middle range, we discover about 325 just detectable steps in loudness. The total number of tones that can be distinguished in any respect—either in pitch or in loudness—is the product of the number of DL's for frequency and the number for intensity. Unfortunately, however, the determination of this product involves more than simply the multiplication of two numbers, for the auditory area (cf Fig 19) is not square, nor is the density of DL's the same in different regions. Therefore, in order to determine the total number of DL's in the auditory area, we find it most convenient to divide the area into small units and find the number for each unit separately.

This procedure is illustrated in Fig 63. The auditory area contained between the threshold of audibility and the threshold of feeling was divided into units, or cells, measuring half an octave in width by 10 db in height. Then the height in DL's of each cell was determined from the data of Riesz (1) and the width, also in DL's, from the data of Shower and Biddulph. These two values were multiplied to give the number of DL's contained in each cell. Then the total number in all the cells was found by addition. These computations reveal that there are about 340,000 distinguishable tones in the entire audible range. Curiously, when the total number of distinguishable colors is deduced from the known number of DL's for hue,

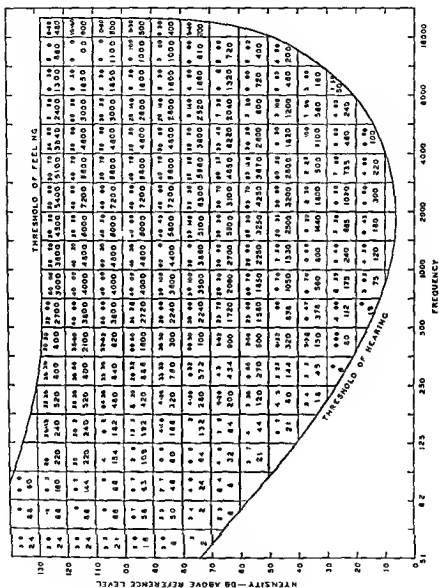


FIG 63 The number of distinguishable tones in the auditory area. The total area is divided into cells whose dimensions in DL's are given by the numbers in the cell. The first number gives the height of the cell in DL's for intensity, the second gives the width in DL's for frequency. The product of these two numbers is written directly below.

brightness, and saturation, the result is of the same order of magnitude

RELATION OF LOUDNESS TO DURATION

When a tone is turned on, its loudness passes through a period of growth before reaching its final value. It may, in some instances, reach a maximal loudness and then decline slightly to a steady state value (Békésy, 3). In general, tones lasting less than half a second appear less loud than tones of the same amplitude whose duration is greater (cf. Békésy, 14).

Lifshitz has proposed an integral law relating loudness and duration. For pure tones of short duration, the law reduces to $I\tau = K$, where I is the loudness level of the sound (in decibels), τ is time in seconds, and K is a constant. This equation states that, in order to maintain constant loudness, the loudness level must be increased by the same proportion that the time is decreased. The author of the law obtained experimental data for times ranging from 0.012 to 0.69 sec and for loudness levels from 34 to 84 db. The data show that within these limits the hyperbolic relation holds. Furthermore, the relation is essentially the same at all frequencies from 50 to 4000 cycles.

These results do not confirm those reported earlier by Békésy (4). He found, for an 800-cycle tone at durations less than 0.1 sec, that constant loudness was obtained when

$$I = k \log \tau + C$$

Here k and C are constants. I is loudness-level (in decibels), and τ is time. The constant k is negative, so that, as τ decreases, I must increase in order to keep the loudness unchanged.

Additional experimental evidence is probably needed to decide between these two functions relating loudness and duration. It should be said, however, that the data of Lifshitz are rather more extensive than those of Békésy.

THE LOUDNESS OF SHORT IMPULSES

When the duration of a tone is made small enough, it reaches a point where we cease to call it a tone and place it in

the class of impulses or short noises. Short noises are a very common sort of sound and are made by an atmospheric disturbance of very short duration. In spite of their short duration they manifest great variety in their subjective aspects. Witness the qualitative difference between the sharp crack due to a spark and the dull boom of distant gunfire. These differences are presumably due to differences in the forms of the sound waves. The loudness of a sound consisting of a single wave is dependent not only upon the amplitude of the wave, as we should expect, but also upon the form of the wave. The investigation of the response of the ear to short impulses should ultimately be of great importance for an understanding of auditory function.

Short impulses of sound are most readily produced and studied by passing brief currents through a transducer. The charge or discharge of a condenser through the transducer, with or without an inductance in the circuit, produces impulses whose form, duration, and amplitude can be controlled. Thus, the discharge of a condenser through a resistance produces a current which rises almost instantaneously to a maximum and then declines according to an exponential curve (see Fig 64). The current declines to $1/2.718$ of its value in a time equal to the product CR , where C is the capacity and R the resistance in the circuit. This product is known as the time constant, T , of the circuit.

A comparison of the loudness of condenser discharges (time constant = 1 msec) with the loudness of a 1000-cycle tone at various amplitudes shows that the loudness of impulses and of tones follows the same law of growth as a function of amplitude, except for small amplitudes (Steudel). Below a loudness-level of 40 db the loudness of the impulses decreased more rapidly than that of the tone, for a given reduction in amplitude. It is especially necessary to employ experienced observers in work of this sort, because of the difficulty of comparing loudnesses in the face of large qualitative differences in the sounds.

Figure 64 shows the effect of duration, as measured by the time constant, T , on the loudness of impulses of fixed amplitude.

As T increases up to 1 msec the loudness grows, for longer durations the loudness remains constant at a value dependent solely upon the amplitude

When a condenser, in parallel with a transducer, is charged through a resistance, the current in the transducer rises according to an exponential curve (concave downward). The loud

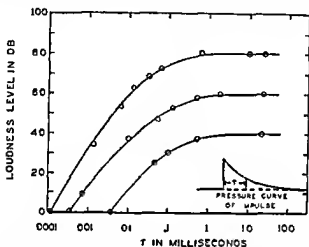


FIG. 64 Showing how the loudness of an impulse varies with its duration. The impulse has a form as shown by the pressure-curve, and a time-constant T , as shown by the abscissa. (After Steudel)

ness of a sound impulse produced by this current depends upon the time constant T in a manner like that shown in Fig. 65. The longer T , i.e., the slower the rise in current, the weaker the sound. If the impulse does not reach two-thirds of its maximal value inside a tenth of a second, no sound is heard.

Another case deserves attention. When the condenser is in a circuit containing resistance and inductance in the proportions proper for making the circuit critically damped, its discharge produces an impulse of the form shown in Fig. 66. Steudel measured the loudness-level of this type of impulse as a function of duration. The duration was measured in terms of the time constant \sqrt{LC} , where L is inductance and C is capacitance. The maximal amplitude of the impulse occurs when $t = \sqrt{LC}$.

The results for a fixed amplitude are shown in Fig 66. With this type of impulse there is an optimal duration for its effect-

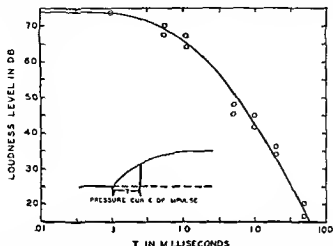


FIG 65 Showing how the loudness of an impulse which rises exponentially depends upon its time-constant. The circles are for two different observers (After Bärck, Kotowski, and Lichte, I)

tiveness in producing loudness—when the maximum of the impulse occurs about 0.2 msec after the beginning of the wave

If impulses like that shown in Fig 64 succeed each other

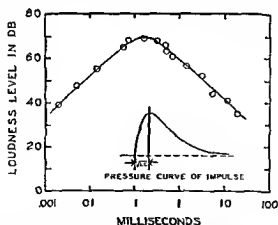


FIG 66 Showing how the loudness of an impulse depends upon its time constant (\sqrt{LC}) whose value is shown on the abscissa (After Steudel)

rapidly enough, the experienced loudness is augmented. As the frequency of the impulses is increased from 1 to 50 per sec-

ond, the loudness-level increases by about 10 db, but further increase has practically no effect. This result checks with the finding that the loudness of a single impulse of given pressure amplitude is about 10 db less than the loudness of a pure tone of the same maximal amplitude.

From these experiments of Steudel's, we may conclude that the ear reacts only to a *change* of atmospheric pressure.

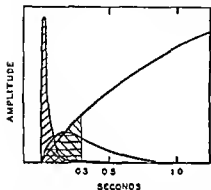


FIG 67 Various forms of impulses having the same loudness. The shaded areas represent the part of the impulse which is effective in producing loudness. (These impulses would not sound the same in pitch.) (After Steudel)

This change must take place within a brief interval of time, but, if the change and its restoration take place too quickly, the ear detects nothing. (Thus a 30,000-cycle tone is inaudible.) Steudel observed that it is the changes occurring within the interval of 0.3 msec which determine the loudness of the impulse. In fact, the loudness is related to the area under the pressure curve contained within this short interval of time, provided the interval contains

the steepest part of the pressure curve. Starting with these notions, Steudel was able to develop an empirical formula for the loudness level of impulses which agrees fairly well with observation.

In particular the formula shows that impulses of many different forms may have equal loudnesses. Figure 67 presents three of these forms whose loudnesses are equal both by actual measurement and by calculation. The shaded areas are the parts of the impulses significant for loudness, according to Steudel's conception.

Although Steudel's empirical formula is adequate for certain situations, there is a more fundamental type of analysis which we should consider. This method of analysis is based on the fact that any wave, such as those in Figs 64 to 67, can be

analyzed into its Fourier components, just as a complex tone may be resolved into a group of pure tones. The difference is that, whereas only certain harmonically related tones will be found present in a complex tone, an impulse of sound can be analyzed into a continuous spectrum of acoustic energy. Thus a sound made by the wave pictured in Fig 65 contains all frequencies within the audible range, but the relative amplitude of these components is smaller at the higher frequencies (cf Fig 39, p 104).

Now, by determining first the spectrum of the sound impulse, and second the sensitivity of the ear to the various frequencies of the spectrum, we might be able to compute the loudness of the impulse. Burck, Kotowski, and Lichte (1) did so, and obtained theoretical curves which agree remarkably well with their own (Fig 65) and with Steudel's measurements (Figs 64 and 66).

The significance of this type of analysis, provided it can be shown to apply to the phenomena we have just considered, is evident indeed. It indicates that, even in short aperiodic stimuli—clicks, pops, cracks, etc.—the ear behaves essentially as an analyzer and evaluates the components of the sound according to the frequency and intensity of the components (cf Fig 117, p 283).

CHAPTER 5

THE OTHER ATTRIBUTES OF TONES

IT HAS been the traditional view of psychology that the attributes of sensation show a one-to-one correspondence to the dimensions of the stimulus. Some such view is also implicit in the naïve epistemology of the physicist. He tends to think of pitch as if it were the perception of the frequency of a tone, but we have seen that holders of that view run into difficulties. The pitch of a pure tone can be altered without changing its frequency, likewise, the loudness of a tone may be varied without changing its intensity. Pitch is a function of the two physical variables, frequency and intensity—loudness is a different function of the same two variables. Both pitch and loudness are fundamentally to be conceived as *reactions* on the part of organisms to sound waves. These are systematic reactions, to be sure, and can be ordered on scales and evaluated, but they are, nevertheless, products of the interaction of an atmospheric disturbance with a living system.

The problem, then, suggests itself as to whether other systematic reactions to pure tones can be obtained from normal observers. Are there additional tonal attributes? Certainly there can be no theoretical, or *a priori* presumption against them, for the number of different functions of the two variables, frequency and intensity, that can be conceived is unlimited (cf discussion by Boring, 4). The only limitation on the number of possible attributes of sensation is a practical one. Differentiation of the sort that can lead to differential neural reaction is not unlimited in the finite organism. We may properly expect to find as separate attributes of tones only those functions of frequency and intensity whose differentiation falls within the resolving power of the organism.

VOLUME

Several writers, during the last century, have disclosed the fact that tones are characterized by an apparent 'largeness' or 'extensiveness' (see Rich, 1). The low tones of an organ appear to be "bigger" than the high chirp of a cricket, even when the loudnesses of the two are equal. This subjective aspect of a tone is known as *volume*. (The radio-engineer speaks of the 'volume of a sound, or of the 'volume control' of a radio set, but he means by volume what we should properly call intensity.)

Rich (1) made the first attempt to bring the problem of volume into the experimental laboratory, by measuring just noticeable differences in volume as a function of frequency. Halverson (3) later measured these differences as a function of intensity. The argument was that, if the DLs for volume are different from those for pitch and loudness, it follows that volume is a separate attribute of tones, since it obeys different laws. Later experiments (Zoll) failed, however, to confirm the independent status of volume when the same technique was used. The results of different experimenters simply did not agree. Nevertheless, throughout all the experiments evidence accumulated from the reports of the observers that, phenomenally, volume is a unique and distinct attribute of tones.

The validity of volume as an attribute was established experimentally (Stevens, 2) by the same method used to determine the isophonic contours of other attributes—the equal pitch contours (Fig 23, p 71), and the equal loudness contours (Fig 45, p 124). The observer was given alternately tones of different frequency, and he varied the intensity of one until it equaled the other with respect to volume. In other words, it is possible to make two tones appear equal in volume when they are obviously different in both pitch and loudness. This result is achieved by making the higher tone more intense than the lower tone. Therefore, we must conclude that the volume of a tone increases with intensity and decreases with frequency.

Equal volume contours, covering a limited range of frequency and intensity, are shown in Fig 68. The slope of these

contours changes with sensation-level in such a way as to indicate that, at high intensities, the relative effectiveness of intensity is greater than that of frequency as a determiner of volume. The reverse is true at low intensities.

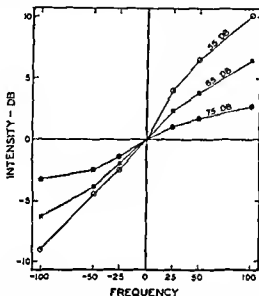


FIG. 68 Equal volume contours, showing how a difference in frequency can be offset by a difference in intensity in order to keep volume constant. The change in intensity is different at different sensation levels (parameter). These curves were drawn from values obtained by subtracting the intensity at which a tone appeared equal in volume to the standard tone of 900 cycles (zero on the abscissa) from the value at which it appeared equal to the standard in loudness. (After Stevens, 2)

The contours of Fig. 68 do little more than establish the possibility of making volumic equations. To this extent they justify the concept of tonal volume, but they leave much to be desired. We should like to know the form of such contours over wider ranges of frequency and intensity, as we do for pitch and loudness. We should like to establish the form of a subjective scale for volume analogous to those for pitch (Fig. 26, p. 81) and for loudness (Fig. 43, p. 118). There is also the difficulty with the present volume-contours that they are slightly sigmoid in form, a fact which means that, when two tones are

each equated to a third tone in volume, they may be found to be not quite equal to each other. Systematic errors, arising from faulty experimental conditions, must be blamed for this discrepancy.

A different sort of experiment was performed by Békésy (9), who estimated directly the apparent diameter of a sound generator placed some distance away. The apparent diameter increased from about 0.9 to 1.5 meters as the intensity of an 800-cycle tone was raised from 10 to 60 db above threshold. At a given intensity a 100-cycle tone appeared larger than the 800-cycle tone. These results show that volume can be readily discriminated under other conditions than those used to obtain the contours of Fig. 68.

DENSITY

The tendency of observers to characterize some tones as being more 'tight,' 'hard,' 'compact,' or 'dense' than others led to an experimental investigation of the possible existence of a fourth attribute of tones (Stevens, 3). Again, observers were presented alternately with two tones of different frequency and allowed to change the intensity of one of them until the two tones appeared equal in *density*. The meaning of the concept (cf. Stevens, 6) was illustrated to the uninitiated observers by presenting them with a high tone (4000 cycles), followed by a low tone (200 cycles). The observers quickly recognized the dense compactness of the high tone as contrasted with the diffuseness of the low tone. When the intensity of a tone was increased, they noticed that the density tended also to increase.

An equal-density contour is shown in Fig. 69. Density is established as a discriminable aspect of tones, distinct from pitch, loudness, and volume, by the nature of this isopsonic contour. Here, the curve is plotted from the *differences* between the values at which two tones are matched in density and the values at which they are matched in loudness, so that the observers could not have confused density with loudness. The fact that they did not confuse density and volume is apparent from the negative slope of this contour as contrasted

with the positive slope of Fig 68. The equal pitch contours are likewise obviously different. The equal-density contour means that for two tones to be equal in density the lower tone must be more intense.

Here, as in volume, we have done little more than demonstrate the existence of a tonal attribute. An unpublished experiment in the Harvard Laboratory has confirmed the form of the density contour for the particular frequencies and intensities

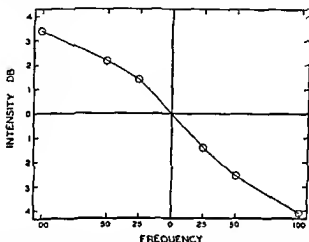


FIG 69 Equal-density contour showing how a difference in frequency can be offset by a difference in intensity in order to keep density constant. The standard tone was 500 cycles (zero on the abscissa) at 60 db above threshold (zero on the ordinate). (After Stevens 3)

employed, but we should like to know more, in a quantitative way, than the general fact that density increases with frequency and also with intensity.

The physiological basis of density and volume is not obvious. One would like to think of density as related to the density of nervous excitation at the cortex. Volume, then, might depend upon the spread of this excitation, as Boring (1) suggested, and loudness might depend upon the total amount. Pitch appears to be related to its location. Such a situation is conceivable, but, in view of our present state of knowledge, it is perhaps wiser to limit ourselves to less speculative assertions. Besides, such

charming simplicity in psychophysiological relations is scarcely to be hoped for. We can say, however, that the interaction of a sound wave with the auditory mechanism of a subject *who has been instructed to observe tonal density* sets up a pattern of neural excitation which is differentiated so as to issue in a discriminatory response. Since the response when the instruction is to judge density is different from the response which occurs when the subject is set to observe pitch, loudness, or volume, it must follow that the total neural event is patterned differently in each case, although the precise nature of the neural pattern and the manner of its arousal by the cochlear mechanism remain obscure.

THE QUESTION OF BRIGHTNESS

The previous discussion has considered only the problem of the attributes of pure tones. The candidacy of any other attribute for recognition as an attribute of pure tones can be successful only when it can be shown that the new attribute is a different function of frequency and intensity from those of pitch, loudness, volume, and density.

Brightness has probably been the most persistent claimant for recognition. It is well known that tones can be characterized as *bright* or *dull*, but this aspect of tones has been said to be so closely correlated with pitch that the two form a single dimension (Troland, 1). Nevertheless, Abraham thought he had demonstrated the independence of pitch and brightness by producing, on a Seebeck siren, tones having the same fundamental frequency, but differing in brightness. He concluded that brightness is a function of the ratio of the size of the hole in the siren disk to the size of the closed interval between the holes.

An analysis, by means of an electrical wave analyzer, shows that the difference between Abraham's tones is a matter of the proportion of higher partials present (Boring and Stevens). Furthermore, the brighter tone is the one with the larger proportion of higher partials present. Further investigation showed that observers agreed in calling the louder of two complex tones the brighter. In other words, brightness was found

to be a joint function of the frequency of the dominant components in a tone and the intensity of the tone. Density, as we have already seen, depends upon frequency and intensity in the same way. This fact suggests the conclusion that density and brightness may be two words for the same attribute.

This conclusion receives further support from the fact that an effort to get observers to equate two *pure* tones in brightness is unsuccessful when the observers are told that brightness is something different from density. On the other hand, observers who are unfamiliar with density are able to make consistent judgments of brightness, and for them brightness turns out to increase with both intensity and frequency, according to the relation which has, with other observers, been established for density. It seems, therefore, that brightness and density vary together to such an extent that the two attributes ought, at least for the present, to be considered identical.

CHAPTER 6

AUDITORY LOCALIZATION

PEOPLE can normally locate with surprising accuracy the source of the sounds they hear. This phenomenon, coupled with the fact that sound does not travel in a straight line nor produce sharp shadows when it passes objects, has led to much experimental research designed to explain our ability to localize. The analogous problem in vision is less puzzling, because one does not see a source of light unless the eyes are turned toward it. Sounds reach the ears, regardless of the direction from which they come, and the cues by which the observer can detect the location of the source are subtle indeed.

Practically all theories of sound localization start from the assumption that the listener observes certain characteristics of the sound which, as he perceives them, vary with the position of the source. Then, by comparing these cues with information derived from past experience with sound sources, he makes a judgment about the location of the source. In order completely to fix the position of the source, he must be able to assign to it three coordinates—its distance and some two angles defining its direction. He can fix the sound only when he can observe at least three of its independent properties which are functions of its position. If fewer than three properties are available, some indeterminateness in localization is certain to arise. If more than three are available, the listener has the possibility of increasing the certainty of his judgment through the use of the additional cues.

Now, these theoretical considerations apply when the observer attempts to locate the source, as regards both its direction and its distance. However, such complete localization of tones, especially of pure tones, is very difficult. The placement of the ears, on opposite sides of the head, often provides an adequate cue for right-left localization, although only meager evidence

for the other coordinates. Consequently, most research has been centered upon the problem of directional localization in the horizontal plane, where the cues consist of differences in intensity and phase (or time of arrival) of the sound at the two ears. Especially has much experimentation sought to evaluate the roles of phase, intensity, and time in sound localization, by means of *dichotic* stimulation, i.e., by leading to the two ears separately sounds differing in intensity, phase, or time of arrival. Many experimenters have sought to determine the relative merits of the 'intensity theory,' the 'phase theory,' and the 'time theory.' Each of these factors—difference of intensity, of phase, or of time—influences localization, each has been nominated by one or more experimenters as the most important factor in localization, and each has been reduced, in theory, to one of the others.

THE ROLE OF INTENSITY

When two tones, differing only in intensity, are led separately to each ear, the listener tends to image the source as

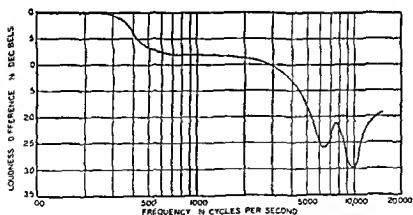


FIG. 70 The difference in loudness-level produced in the right ear when a source of pure tone is moved from the right to the left of an observer. The curve shows how marked is the sound-shadow produced at different frequencies by the head. (Steinberg and Snow)

located toward the side of the greater intensity. It should be emphasized, however, that this form of stimulation corresponds,

in general, to no actual source of sound. An actual source would produce differences of phase as well as of intensity. Nevertheless, the tendency for the imagined source to shift to the side of the greater intensity is often very compelling.

When an actual source of sound is situated at the side of an observer, a difference of intensity occurs at the two ears, for one ear finds itself located in the shadow of the head. In a tone, the sharpness of this shadow is a function of frequency. Very low tones produce practically no shadows, but, when the frequency is greater than 5000 cycles, the difference in loudness-level at the two ears may be as great as 30 db. Figure 70 shows the difference in loudness-level at the two ears when

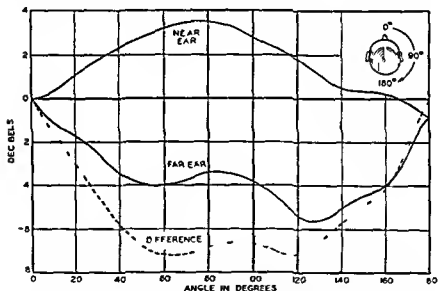


FIG. 71 The variation in loudness-level as a speech-source is rotated in a horizontal plane around the head. The dotted curve shows the difference in loudness-level between the two ears for various azimuths (Steinberg and Snow)

tones of various frequencies come directly from the side (azimuth of 90°). The difference may be even greater for other azimuths (Sivian and White). It is clear from Fig. 70 that when the sound is complex, such as speech or music, not only is there a difference of intensity at the two ears, but a difference

in composition as well. The high frequency components are lost to the ear on the far side of the head.

Calculation of the average loudness-level of speech at the two ears, for various positions of the source, gave the results shown in Fig 71 (Steinberg and Snow). At 42° and 137° the difference in total loudness is the same, but the quality of the speech is different at the two ears, because the function relating loudness to azimuth is not the same at all frequencies. In the first place, the ears are not diametrically opposite, but are about 165° apart, and, in the second place, the external

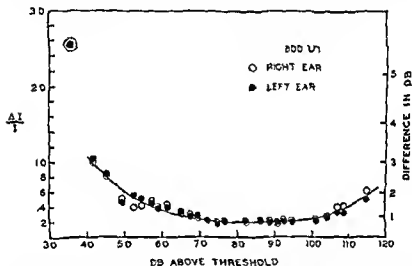


FIG. 72 Showing the amount (ΔI) by which a tone (800 cycles) in one ear must be made more intense than the same tone in the other ear in order to produce a just noticeable shift of the apparent source from the medial plane (After Upton)

ear flap casts a noticeable shadow at high frequencies, with the result that sounds originating behind the head suffer a different distortion from those originating in front.

In the laboratory situation, where tones differing only in intensity fall on the two ears separately, the apparent source is displaced laterally, whenever the difference exceeds a certain threshold value. Fig 72 shows how large this difference must be (Upton). The value ΔI was found by measuring the

amount by which the intensity of an 800-cycle tone in one ear had to be increased to cause a shift of the apparent source of sound from the median position. These results represent a certain type of differential sensitivity, they should be compared with the curves in Fig 54 (p 138). The smallest ratio of ΔI to I obtained by Upton's dichotic method is about twice as large as that for the monaural method used by Riesz, when the intensity, in both cases, is stated in terms of the energy of the stimulus. (Care must be taken, in comparing the ratio $\Delta I/I$ in different experiments, to be sure that the units in which I is measured are the same. Thus the values reported by Upton need to be transformed from units of pressure to units of energy, before they can be compared with those of Riesz, because energy is proportional to the square of the pressure.)

As the difference in intensity at the two ears is increased beyond the minimal value necessary to displace the sound from the median plane, the apparent source moves farther to the side. Stewart (3) reported that the angular displacement of the apparent source is proportional to the difference, in decibels, between the intensities in the two ears. However, it is improbable that such a simple relation obtains for all frequencies and intensities. Some of Stewart's observers showed great variability in their results, and with some of them the intensity-effect was completely absent.

THE ROLE OF PHASE

When two tones, differing only in phase, are led one to each ear, the listener tends to image the source as located toward the side of the leading phase. A phase-difference means that the crest of one sound wave arrives at its receptor before or after the crest of the other wave.

Clearly, if a sound wave comes from the side, the crest of a particular wave reaches the nearer ear before it reaches the ear on the far side of the head. But, when the sound is a continuous tone consisting of successive waves, the situation may become ambiguous, for when the phase at one ear leads the phase at the other ear by more than 180° it can be said no longer to lead,

but to lag. This situation may arise whenever the difference in the length of the path to the two ears is greater than half of the wave length of the sound, for then there is a position of the source on *both* sides of the head which will give the same phase difference at the two ears. Thereupon, phase becomes an ambiguous cue for localization.

These considerations indicate that, for high frequencies, where the wave length is short, localization based on phase differences should break down. The critical frequency for this break-down can be readily calculated. It is the frequency whose wave length is just twice the distance between the ears, which are about 21 cm apart. This frequency turns out to be about 800 cycles. With any higher frequency there are positions both on the right and the left sides of the head at which the source could be placed to yield identical phase-differences.

Much effort has been expended in trying to evaluate the effects of phase by leading tones of different phase to the two ears. Although it is possible to obtain lateral displacement of the apparent source when the phase at one ear is advanced or retarded, the results of these experiments show great inconsistencies. Typical is the finding that some observers show a 'phase-effect' whereas others show no effect at all, even under identical conditions (Wightman and Firestone). When listening to binaural beats where the phase relations at the two ears undergo continuous change, most observers notice no apparent shift in localization unless the change is suggested to them. Thus it appears that the listener's attitude is of great importance (Valentine).

The upper limit in frequency at which the 'phase-effect' is detectable has been placed at values ranging from 512 cycles to 17,000 cycles (Trimble, 1). The fact that the refractory period of the fibers in the auditory nerve limits the frequency at which each fiber can respond to each sound wave suggests that the 'phase-effect' should cease at frequencies greater than about 800 or 1000 cycles (see p. 398). At any rate, a similar prediction appears to hold true regarding binaural beats, which are not detectable above that range of frequencies (Stevens and Sohler).

THE ROLE OF TIME

As already pointed out, phase difference means that the crest of a sound wave arrives at one ear before it arrives at the other. When the sound consists of a single sharp sound wave, such as a click, we customarily speak of its time of arrival at the two ears rather than its phase. When two sound impulses differ in time at the two ears by the proper amount, the apparent source tends to shift to the side of the first arrival. There is, of course, a minimal value of the time difference below which no displacement occurs. And there is another value above which the sound breaks up and appears double—one sound at each ear. The lower value is of the order of 0.1 msec and the upper value is of the order of 2 msec, although some authors have reported values quite different from these (cf Trimble, 2). Between these values, the apparent displacement of the sound source is roughly proportional to the time difference (Trimble, 3, Bekésy, 5).

Under the proper conditions, when a difference of intensity is apposed with a temporal difference in the two ears, the two tendencies to lateral localization may cancel one another and leave the apparent source of sound in the median plane (Trimble, 4, see also p. 427).

THE CUES TO DISTANCE

We have seen that, for the lateral localization of tones, differences in intensity and phase at the two ears provide serviceable cues, for clicks the cues are differences in intensity and time. What are the cues by which we judge the distance of a source of sound?

The total intensity of a sound is a cue to its distance, provided the sound is a familiar one. However, more interesting cues, theoretically, are those based on the combined intensity and phase relations at the two ears. These relations change with the distance of the source from the observer, even when the direction of the source remains the same. The effect of distance can be conveniently measured with a man-shaped dummy whose ears have been replaced by microphones. Figure 73

shows the amplitude ratio (measured in terms of sound pressure) and phase difference at the two ears of such a dummy. The stimulus is a 256-cycle tone, placed at the direction or azimuth indicated by the abscissae, and at distances from the center of the head as marked on the curves (Wightman and

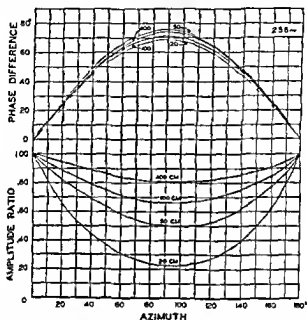


FIG 73 Showing the differences in intensity and in phase produced at the two ears when a 256-cycle tone is sounded at various azimuths and distances (After Wightman and Firestone)

Firestone) These curves agree well with the curves that Hartley and Fry computed on the assumption that the head is a rigid sphere

The phase-difference depends upon the azimuth, but its dependence on the distance of the source is slight, and, owing to the random reflection of sounds from the shoulders, it is erratic. There is, however, a less ambiguous relation between the amplitude ratio and the distance of the source. This ratio depends on both the distance and the azimuth. Therefore, we might expect theoretically that, with the knowledge of phase-difference to determine the direction of the source, the additional

knowledge of the amplitude ratio would enable one to determine the distance of the source. Even without a knowledge of the direction, a knowledge of the amplitude ratio should enable a certain limiting distance to be fixed. At this frequency of 256 cycles, for instance, an amplitude ratio of 0.40 would indicate that the source is certainly within 50 cm of the head. The curves show that this method of determining the distance of a source can be accurate only when the source is within about 100 cm of the head and at the side, for it is only then that the amplitude ratio changes appreciably with distance.

Wightman and Firestone presented 256-cycle tones, differing in amplitude and phase at the two ears, and investigated the accuracy with which naive observers could localize them as to direction and distance. Some of the observers were consistent in judging azimuth, but none of them was able consistently to estimate distance. Hence, it appears that observers are not, in general, able to utilize the slight cues with which they might judge distance from differences in phase and intensity at the two ears.

THE LOCALIZATION OF ACTUAL SOURCES

The previous discussion has dealt with the problem of auditory localization by analyzing the factors which provide cues as to the position of the source. We have considered the ability of a listener to assign an apparent direction to a sound when it is led to his ears dichotically, but there remains the problem of the accuracy with which actual sounds in free space can be localized. It is true that this latter problem was historically the first to be investigated, but interest in it was largely eclipsed by the activity of those studying the effects of artificial dichotic stimulation under laboratory conditions.

The earliest systematic investigations of localization were carried out by means of 'sound cages'. These were convenient devices for holding a source of sound at any desired position about the head of a subject, whose task it was to indicate the direction from which the sound came. The results of these investigations were limited by the fact that, owing to the lack

of electrical generating apparatus, it was necessary, for the most part, to use clicks and noises as stimuli. Another limiting factor was the custom of experimenting in closed rooms whose walls were not sound absorbent, and which reflected sound from many directions at once. In spite of these drawbacks, certain facts were early established (Pierce). Observers are able (1) to locate noises better than tones, and (2) to distinguish right from left with great accuracy. However, they tend (3) to confuse the location of sounds lying in the median plane, and (4) to distinguish with the least accuracy small changes in the azimuth of sounds coming directly from the sides. This last finding is predictable from the curves of Fig 73. Near the azimuth of 90° there is a range of about 30° throughout which the phase and intensity relations at the two ears change practically not at all. Within this range all cues for localization must appear alike to the listener.

One condition necessary to a successful study of the ability of a listener to locate an actual source of pure tone is that all the tone should reach the ears directly from the source and none of it from reflecting surfaces. An attempt to satisfy this condition was made by seating the observer in a tall swivel-chair on top of a high ventilator rising above the roof of a building (Stevens and Newman, 1, 2). The tones were generated in a loud speaker mounted on the end of a 12 ft arm attached to the pedestal of the chair. In this way, the source could be moved noiselessly in a complete circle at the level of the observer's ears. Since confusion between right and left seldom occurs, the subject of the experiment was required to name from which of thirteen positions, spaced 15° apart on his right side, the tone appeared to emanate. The average of the errors made by two observers is plotted in Fig 74, plot A. (It was not counted as an error if the listener confused positions in the front quadrant with those in the rear quadrant.) The errors are relatively constant at low frequencies, but become definitely larger as the frequency of the tone approaches 3000 cycles. Above 4000 cycles, however, localization improves again and is quite as accurate at 10,000 as at 1000 cycles.

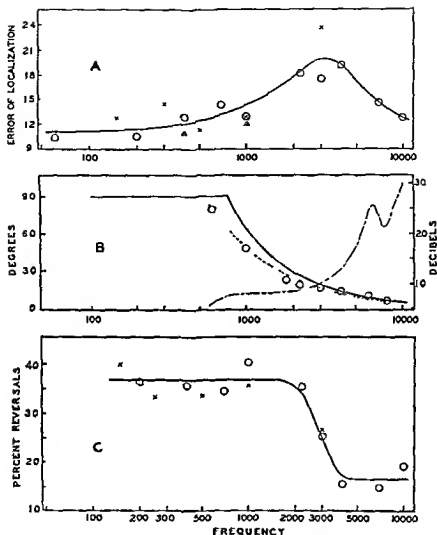


FIG. 74. Plot A shows the average of the errors, in degrees, made by two observers in localizing a source of tone at various frequencies. Circles and crosses are for two different series of observations. Triangles are for impure tones.

Plot B shows the absence of phase-effect at high frequencies and of intensity effect at low frequencies. The solid curve represents theoretically the maximal angle by which a tone can be displaced from the median plane by 180° change in phase. The circles on the dotted curve represent what Halverson (4) reported as the observed limit of displacement. The dot-dash curve represents the observed difference in intensity at the two ears of tones originating at the side of the head (Sivian and White).

Plot C shows the percentage of confusions between front and rear quadrants (Stevens and Newman, 2).

The explanation of the shape of the curve in plot *A* must concern us. The inexact localization of tones between 2000 and 4000 cycles is precisely what we should expect from a consideration of the effects of the two localizing factors, difference in phase and in intensity. Owing to the size and shape of the head, there are, as already pointed out, theoretical limits to the possible effectiveness of each of these factors. These limits are shown graphically in plot *B* of Fig 74. It is well established that phase difference is most effective in determining the apparent location of low tones, and that, above some frequency in the neighborhood of 800 cycles, its effectiveness decreases with increasing frequency. The solid curve in plot *B* represents, theoretically, a first approximation to what is the maximal lateral shift in localization obtainable with a phase difference of 180° . In other words, it shows how far from the median plane a tone of a given frequency would have to be to produce a phase-difference of 180° . The dotted line shows the results reported by Halverson (4) when he measured the apparent displacement of the source by leading tones to the two ears 180° out of phase. Clearly, then, phase is an effective cue for localizing low tones, but is ineffective for high tones.

It should be noted in passing that Halverson's results are in conflict with the results of Stevens and Sobel, who failed to detect binaural beats at frequencies above 800 cycles. Indeed, it is difficult to conceive how phase differences could possibly produce displacements of the apparent source at very high frequencies, in view of the fact that the ability of the impulses in the auditory nerve to synchronize with the frequency of the stimulus breaks down at high frequencies (see p 394 and p 421). It may be that Halverson's results were due to changes of intensity rather than of phase.

The dot-dash curve of plot *B* represents the observed differences in intensity at the two ears of tones originating at the side of the observer (see Fig 70). These differences are small at low frequencies, but above 4000 cycles they increase rapidly. In other words, relative intensity provides a good cue for localizing high tones, but not for low tones. In the region near

3000 cycles, neither relative intensity nor phase offers very adequate cues, and it is precisely in this region that the errors of localization are greatest, as shown in plot *A*

Another interesting difference in the localizability of high and low tones occurs in the matter of front back discrimination. Plot *C* of Fig 74 shows the percentage of confusions of the front back quadrants which occurred in the experiment we are considering. It is apparent at once that the total range of frequencies is divided into two distinct regions separated by a critical region near 3000 cycles. For low tones, where localization is based on phase differences, discrimination between the front and back quadrants is only a little better than chance. Above 4000 cycles the number is but one third of those expected by chance. Apparently the ability to distinguish front from back in high tones is due to a difference in intensity between sounds in front and behind.

A number of checks were made to validate this notion. A continuous tone of 10,000 cycles, when swung in a circle completely around the listener, appeared much weaker behind the listener than in front of him. Then, a number of tests were made in which the actual intensity of the tones was varied from trial to trial, with the result that the number of confusions increased over that usually found for low tones. It appears that the observer is able to form a subjective standard of intensity in a very few trials, and afterwards the tones heard behind are the weak ones and those heard in front are the strong ones. Sound shadows from the external ear must account for this effect.

In view of these findings, it is no longer surprising that complex tones and noises can be localized with relative ease. When both low and high frequencies are present as components in a sound, the low frequencies provide cues in the form of phase-differences and the high frequencies provide cues in the form of intensive differences, and the two types of cues render each other mutual support. In addition, the attenuation of the high frequencies, in sounds coming from behind the listener, changes their quality as well as their loudness. The result is

an accuracy of localization greater than that obtainable with pure tones

The remarkable effectiveness of changes in the quality of complex sounds for localization when the direction of the source changes is shown by the ability of a person, deaf in one ear, to localize familiar complex sounds. That these changes actually contribute to sound localization is supported by experimental evidence. In fact, for complex sounds, the accuracy does not differ greatly when the localization is made monaurally instead of binaurally (Angell and Fite)

THE FACTOR OF MOVEMENT

Our concern thus far has been with static localization, i.e., the localizability of tones coming from a fixed direction. When no relative movement occurs between the observer and the source, the ability of the observer is, for the most part, limited to the designation of how many degrees a sound is from the median plane, and localization relative to other planes is extremely difficult, especially for low tones. However, most actual cases of localization involve an additional dynamic factor of movement. When we go hunting for a song bird whose music attracts us, we are free to move our heads, and thereby add materially to our cues for localization.

The effectiveness of movement can be illustrated by considering the simple case in which the listener is allowed to move his head from right to left in the horizontal plane. He should then be able to tell front from back in the median plane, for, if the tone is in front and he turns to the left, the tone will appear to be on the right side of his head, whereas, if he turns to the right, the tone will appear on the left side. The opposite would be true if the tone were behind him. If the tone were directly overhead, moving the head would not alter the relative phases or intensities at the ears, and this fact would be the cue to the location of the source. Similarly, other positions of the source would produce binaural differences which movement of the head would alter in some characteristic fashion.

THE STEREOPHONIC EFFECT

A novel attack on the problem of localization, one that has only recently been initiated, is the investigation of auditory perspective the stereophonic effect of multiple sources of sound

When listening directly to an orchestral production, the audience senses the spatial relation of the various instruments of the orchestra This spatial character of the sounds gives to the music a characteristic of depth and extensiveness Ideally this auditory perspective should be preserved when the music is reproduced—by radio broadcast, for example—but when a single microphone is used to pick up the music, the possibility of re-establishing the binaural differences which would make for perspective in the reproduction is lost

There are two ways of reproducing sounds in true auditory perspective One is binaural reproduction in which there is led to the observer's ears by means of earphones an exact copy of the sound waves which would stimulate his two ears if he were listening directly We can do this conveniently by picking up the sound with two microphones, placed in the position of the ears on a man shaped dummy and connecting one ear phone to the amplified output of each microphone Then, if someone walks around the dummy, talking as he goes a person wearing the earphones has a compelling illusion of someone walking around him The other method uses two or more microphones and a corresponding number of loud speakers, and aims to reproduce in a second room an exact copy of the pattern of sound vibration that exists in the original room

Ideally, an infinite number of microphones and loud speakers of infinitesimal dimensions would be needed to make the reproduction perfect, but, in practice as few as two microphone loud speaker combinations (channels) have been found to give fair auditory perspective Extensive tests were carried out with two and three channels in various combinations in order to determine the adequacy of such methods (Steinberg and Snow) Figure 75 shows a diagram of the experimental set up and the results obtained The microphones were set on a 'pick up'

stage and the loud speakers were placed at the front end of an auditorium, behind a curtain of theatrical gauze. The average position of a group of twelve observers is indicated by the cross in the rear part of the auditorium. These observers were asked

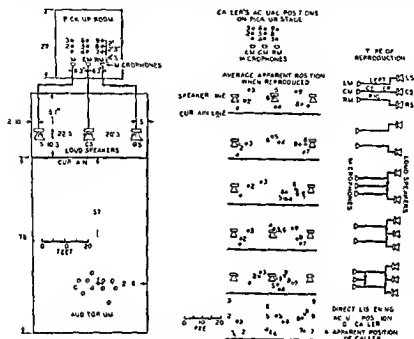


FIG. 75. Diagram of arrangement (left) for tests of the stereophonic effect, and (right) the results obtained. (Steinberg and Snow)

to indicate from what point behind the curtain the sound (speech) appeared to come, and their judgments were compared with the actual positions on the 'pick up' stage.

With three-channel reproduction, there is reasonably good correspondence between the caller's actual position on the 'pick-up' stage and his apparent position on the virtual stage, both as regards right and left, and front and back. Thus the system affords depth as well as angular localization. For comparison, there is shown in the last diagram the localization obtained by direct listening. The crosses indicate the caller's position behind the curtain and the circles indicate his apparent position, as judged by the observers listening to his speech directly.

With two-channel reproduction, the virtual stage tended to appear wider and less deep than with three-channel reproduction.

Steinberg and Snow showed that the accuracy of the angular localization under these conditions can be accounted for by a consideration solely of the loudness-differences at the two ears of the observers. Indeed, it is difficult to see how phase differences could, in multi-channel reproduction, assist the localization in any way. The angular location of each position on the virtual stage results from a particular intensive difference at the two ears produced by the speech coming from the loud speakers. The factors influencing depth localization are not, however, so simply apparent. It has been shown that, even with single-channel reproduction, an increase in the ratio of the sound reaching the microphone directly to that reflected to the microphone from the walls causes the sound to appear closer to the listener. In other words, more reverberant sound is heard when the source is farther away in the room (Maxfield). This point is of practical importance to motion picture engineers.

If the quality of the sound from the various loud speakers in the multi-channel arrangement differs noticeably, it has important effects on localization. When the two-channel microphones were so arranged that one picked up mostly direct and the other mostly reverberant sound, the virtual source was localized exactly at the 'direct' loud speaker, until the power from the 'reverberant' loud speaker was from 8 to 10 db greater. In general, localization tends toward the channel giving the most natural reproduction, and this effect can be used to aid the loudness-differences in producing angular localization.

CHAPTER 7

AURAL HARMONICS AND COMBINATION-TONES

WHEN the ear is stimulated by a pure tone, we hear, not only that tone, but also a series of harmonics, or overtones, whose frequencies are multiples of the frequency of the original tone. Although traditionally these overtones have been called 'subjective harmonics,' the fact that they are generated by a physical process in the ear itself makes it proper to refer to them as *aural harmonics*. When, for example, a pure tone of 500 cycles is sufficiently intense, a well trained ear has no difficulty in detecting a pitch corresponding to 1000 and to 1500 cycles. Likewise, when two loud tones are sounded together, we hear, in addition to these primaries, a group of *combination tones* made up of frequencies which are the sums and differences of the frequencies of the two primaries and of their several harmonics. We shall see, in this chapter, to what extent it is possible to measure these various tones, and to account for their presence in terms of the nonlinearity and asymmetry of the auditory mechanism.

INDIRECT MEASUREMENT OF AURAL HARMONICS

It is obviously impracticable to measure the intensity of an aural harmonic simply by listening to it. In fact, many times listening does not even reveal the presence of the harmonics. They can, however, be discovered and measured when an auxiliary tone is introduced at a closely adjacent frequency and allowed to beat with the aural harmonic. These beats usually are noticeable even when the individual harmonic is obscured by a louder fundamental. Thus, the fourth harmonic of a 500-cycle tone, 80 db above threshold, may not stand out by itself, yet, when a frequency of 2003 cycles is introduced, faint beats will be heard at the rate of 3 per second. Furthermore,

since beats are strongest when the intensities of the beating tones are equal (see Chapter 9), we have reason to believe that the most noticeable beating will occur when the intensity of the 2003-cycle tone equals that of the aural harmonic. Therefore, by adjusting the strength of the auxiliary tone until the best beats are heard, we can obtain a fair indication of the mag

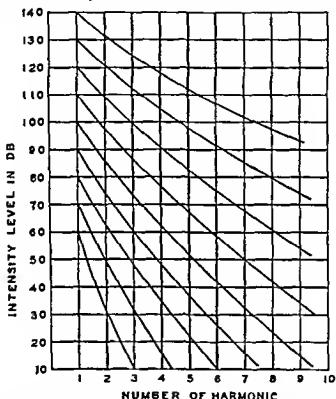


FIG 76 Showing the intensity level of the various aural harmonics when the fundamental (first harmonic) has an intensity as indicated

Example when the intensity level of the first harmonic, or fundamental is 100 db the intensity levels of the successive higher harmonics are 86 73, 62 52 42 etc., db (After Fletcher, 2)

nitude of the harmonic generated in the ear. Combination tones also yield to this method of attack, and it is possible to demonstrate the presence of large numbers of them when two loud tones are sounded (Wegel and Lane)

Using this method of 'best beats,' Fletcher (2) was able to construct the curves shown in Fig 76. Here we have a set of

functions giving the relative intensities of all the harmonics generated in the ear in response to stimulation by a pure tone (first harmonic) of known intensity-level. In drawing these curves, Fletcher made the reasonable assumption that the amount of distortion imposed upon a tone during its transmission through the middle ear is dependent only upon the intensity-level of the sound, and not upon its sensation-level. Hence, the relative size of the harmonics is independent of the frequency. In utilizing these curves we must remember that they are somewhat idealized, and that any individual case is likely to vary considerably from these values. Nevertheless, Békésy (17) made some measurements on a 200-cycle tone which agreed very well with the prediction of Fig. 76.

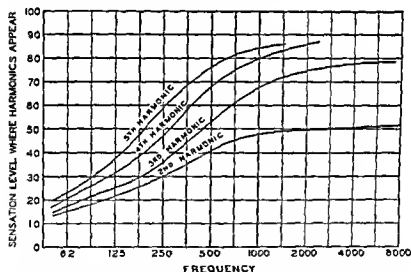


FIG. 77. The sensation level at which the various harmonics of different fundamental frequencies first appear as the intensity is raised from zero (After Fletcher, I. Courtesy of D Van Nostrand Company, Inc.)

One important consequence of the dependence of the size of the aural harmonics on the intensity-level is seen when we translate these intensity-levels into sensation-levels. Owing to the form of the curve for the threshold of audition (Fig. 17, p. 50), a given intensity-level represents different sensation-

levels at different frequencies. Hence, when we express the magnitude of the aural harmonics of a 60-cycle tone in terms of sensation-level, we find that, for a fundamental at an intensity-level of 100 db, the sensation-levels of the first five harmonics are 44, 46, 44, 38, and 30 db. The second harmonic has a higher sensation-level than the first.

Not only are the subjective effects of aural harmonics more prominent for low tones than for high, but the harmonics first make their appearance at a lower sensation-level when the frequency of the fundamental is low. Figure 77 shows the sensation-level of the fundamental at which the various harmonics first become detectable (Fletcher, 1). In order to obtain these curves, the pure fundamental tone was sounded at various levels and the presence of the harmonic was determined by means of an auxiliary tone which beat with the harmonic. For tones above 1000 cycles, no harmonics are generated until the sensation-level is about 50 db above threshold.

DIRECT MEASUREMENT OF AURAL HARMONICS

Our approach to the problem of aural harmonics in human ears is at best indirect, and the results of measurement are variable and sometimes of equivocal significance. A more direct attack is possible in the ears of animals, for there we can record and analyze the electric potential generated in the cochlea as a response to auditory stimulation. The nature of the cochlear potentials is the subject of Chapters 13 and 14, but for present purposes it is sufficient to point out that, whenever a sound-wave enters the ear, it is transformed into an electric wave of nearly the same form. (The microphone used in radio broadcasting performs precisely the same transformation of sound into electrical energy.) The cochlear microphonics can be picked up by electrodes placed in contact with the exposed cochlea of an animal and amplified for purposes of study. Thus, with one electrode near the round window of the cochlea and the other in contact with some other part of the animal, we obtain a potential which may be taken as an index of the effective sound-energy reaching the end-organs of the auditory

mechanism. Then, with a wave-analyzer (Chapter 1), which can be tuned to respond separately to each component of the electric potential, we can measure the amplitude of the fundamental and of each aural harmonic as it exists within the cochlea (Stevens and Newman, 3).

Typical results, obtained from a cat and from a guinea-pig, are shown in Figs. 78 and 79 respectively. The ear was stim-

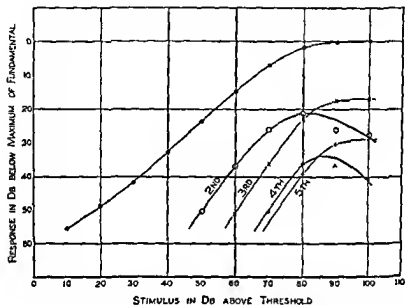


FIG 78 Analysis of the cochlear microphonics obtained from a cat's ear when stimulated by a pure tone of 1000 cycles. Abscissa values represent the intensity of the stimulus in decibels above the average human threshold. The uppermost curve shows the magnitude of the fundamental frequency in the cochlear microphonics, and the other curves are for the higher harmonics, as indicated. (Stevens and Newman, 3)

ulated by a pure tone, and the relative magnitude of the fundamental and of each of the harmonics in the electric potential picked up from the cochlea was measured by the wave-analyzer. In each case the stimulus was a very pure tone of 1000 cycles, whose intensity is represented along the abscissae. The magnitudes of the different components of the cochlear microphonics are plotted as ordinates against the stimulus-intensity. The fundamental has the greatest magnitude. It is represented

by the line connecting the solid black dots in the figures. It will be seen that the fundamental increases almost linearly until it is about 20 per cent of its maximal value, or about 15 db below the maximal value. From this point on, an increase in the strength of the stimulus gives a proportionately smaller and smaller increase in the response of the cochlea, until finally the maximum is reached. Any further increase in the stimulus

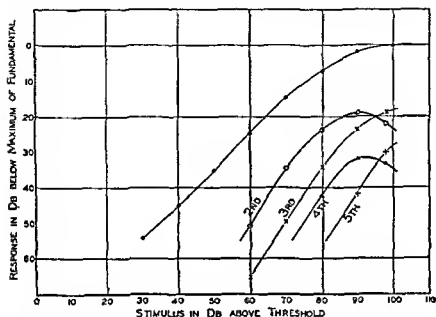


FIG 79. Analysis of the cochlear microphonics obtained from a guinea pig's ear. (Similar to Fig 78) (Stevens and Newman, 3.)

results possibly in an increase in the size of the harmonics, but may soon lead to permanent injury of the ear.

When, at any point along this curve, such as, for example, the 70-db sensation-level, the remainder of the potential is analyzed, we find present the second harmonic with a magnitude, represented by the open circles in the figures, usually 15 to 20 db below the fundamental; the third harmonic, represented by the crosses, 10 to 15 db lower; and the fourth and fifth harmonics still lower. The same analysis is repeated at the other sensation-levels.

It should be noted at once that, below a sensation-level of

about 50 db, the magnitude of all aural harmonics is so small that they lie below the limit of our ability to measure them, just as they do in the human ear at this same frequency of 1000 cycles (Fig 77) Above this level the harmonics increase with an increase in the intensity of the stimulus, but they grow even more rapidly than the response of the fundamental They increase, not only in absolute magnitude, but also in the relative proportion that they are of the total response—a fact consistent with the curves of Fig 76 However, whereas the odd numbered harmonics, the third and the fifth, appear to reach a maximum beyond which they fail to increase, the even harmonics, the second and fourth, not only reach a maximum but decline substantially at higher intensities, both in absolute and in relative magnitude

The results reported for 1000 cycles are thoroughly typical of those obtained at other frequencies (Newman, Stevens, and Davis) This fact is easily demonstrated at higher frequencies, but the interpretation of experiments on lower frequencies requires the evaluation of certain factors In the first place, at frequencies below 1000 cycles there is usually present a large amount of disturbance created by the electrical activity of the auditory nerve These so-called action potentials tend to distort the wave form of the cochlear microphonics and thereby introduce spurious harmonics In the second place, the sensitivity of the ear is different at different frequencies, so that, as we have just seen, there is a difference between the intensity level and the sensation level of a sound Since the potential generated in the cochlea is a measure of the sensation level of the effective stimulus, rather than of the intensity level, we obtain apparently greater distortion at the low frequencies In other words, at low frequencies the harmonics are relatively more prominent, because the ear is more sensitive to them than to the fundamental

ODD VERSUS EVEN HARMONICS

It is evident from Figs 78 and 79 that the odd and the even harmonics behave quite differently Not only do the even

harmonics pass through a maximum as the intensity of the stimulus is increased, but they also tend to show great variability under experimental tests. The odd harmonics are generally more stable and can be measured with greater reliability.

An important example of the ease with which the even harmonics can be modified experimentally occurs in some measurements on a guinea pig. This animal shows, under anesthesia, a convenient disposition to contract spasmodically the muscles in its middle ear. These contractions demonstrate that the muscles are able to function, and there is reason to believe that, between the contractions, the muscles maintain something like normal tonicity. Additional anesthesia may abolish both the contractions and the "normal" tonicity. What, then, is the effect of tension of the muscles of the guinea pig's ear on aural harmonics? Figure 80 presents a comparison of the results

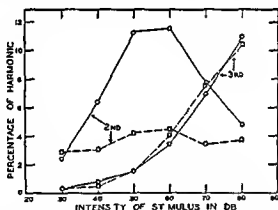


FIG 80 Showing how a change of tonus of the muscles of the middle ear of a guinea pig affects the second and third harmonics. Each curve is an average of values for stimuli of 1000, 1750, and 2500 cycles. The abscissa gives the intensity of the stimulus referred, for each frequency, to the intensity necessary for 0.1 per cent of the maximum response of the fundamental. The dotted curves show the amount of harmonic remaining after the muscles are relaxed. (Stevens and Newman, 3)

obtained, first, in a "normal" condition (i.e., while the tensor was contracting occasionally), and, second, after the contractions had ceased. The sizes of the harmonics under the condition of tonus are shown by the solid lines, and the sizes under relaxation by the dotted lines. It is clear that the size of the

second harmonic is markedly reduced, whereas the magnitude of the third harmonic remains essentially unaltered (Some of this change in the second harmonic may have been due to the behavior of action potentials, or to other factors difficult to evaluate)

With the cat, no such convenient spasm occurs in the middle ear. However, the cat's tensor tympani muscle can be exposed, so that the tendinous attachment of the muscle can be cut at a point near the eardrum. Results of this operation are shown in Fig 81. The solid curves represent again the normal condition,

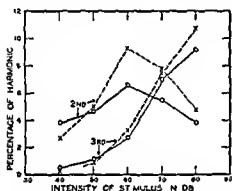


FIG. 81 Effect of cutting the tensor tympani of a cat upon the magnitude of the second and third harmonics. The coordinates are the same as those in Fig 80. The dotted curves show the amount of harmonic present after cutting (Stevens and Newman 3)

whereas the broken lines are for values measured after the muscle had been cut free. Here again the second harmonic has been markedly altered, but the third harmonic exhibits its usual stability.

Now, it is not entirely unexpected that the odd and the even harmonics should be independently variable. In any transmission system producing distortion, as in the middle ear, the characteristic which gives rise to

the even harmonics is separate from that which produces the odd. A system which is nonlinear, but symmetrical, generates only odd harmonics, as when amplifying tubes are connected in 'push pull'. A system which is asymmetrical furnishes us with even harmonics. Consequently, we are forced to conclude that the ear is both nonlinear and asymmetrical, and that the degree of asymmetry is subject to experimental control. These notions form the basis for the discussion, in the next section, of the characteristic curve of the ear.

It should be pointed out here again that part of the variability

in the behavior of the even harmonics at low frequencies is due to the admixture of action potentials among the cochlear potentials. The action potentials tend to appear as even harmonics when viewed through a wave analyzer.

THE TRANSMISSION CHARACTERISTIC OF THE EAR

The behavior of aural harmonics suggests a definite hypothesis of their origin. With sounds of small amplitude, the response of the ear is essentially linear and symmetrical, so that no harmonics occur below an intensity level of about 45 db. As the intensity is increased and the auditory mechanism is made to vibrate with larger amplitude, first one portion of the mechanism and then another reaches a constraining limit beyond which Hooke's law breaks down. (Hooke's law tells us that, in a linear system, the resulting displacement is proportional to the force applied.) When the displacement passes such a limit, the function relating sound pressure to the response of the ear is distorted from linearity. It is the graph of this function which is referred to by the term *characteristic curve*, a term widely used in describing the properties of vacuum tubes. Then the position of the system on such a curve, when no force is applied, is called the *operating point*, and under a sinusoidal force, the system moves back and forth along the characteristic curve on either side of this point of rest. An example of a characteristic curve is shown in Fig. 4 (p. 14).

When the curve is symmetrical on both sides of the operating point, nonlinearity leads exclusively to the production of odd harmonics, and the even harmonics arise only when some degree of asymmetry occurs. Consequently, the simplest hypothesis regarding the behavior of the ear would hold that, when a sinusoidal pressure is impressed on the ear and its amplitude is gradually increased, the peaks of displacement in one direction soon reach a limit beyond which the characteristic curve becomes bent. At this point even harmonics appear. The amount of even harmonics will increase, and at some greater amplitude the peaks of displacement in the opposite direction

also arrive at a point where linearity stops. Here begins the production of odd harmonics, for here the movement of the ear encounters nonlinearity in *both* directions at once.

The differences we have noted between the odd and the even harmonics, with respect both to magnitude and to variability, can be accounted for in terms of this scheme. Particularly important is the fact that this hypothesis enables us to explain how a marked modification of the even harmonics might be produced by a change of tension in the muscles of the middle ear. If we conceive of the two limits of linearity as being relatively fixed, it is clear that a pull from the muscles of the ear might shift the operating point along the characteristic curve and leave it in some new relation to the mid point between the limits. Then, as experiment has suggested, changes in the tension of these muscles might increase or decrease the relative amount of even harmonics.

These relationships can most easily be understood if we construct an approximation to the over all characteristic curve of the ear (Fig. 82). We must plot the curve for the response of the fundamental, as is shown in Fig. 78. However, we must plot it in linear instead of logarithmic coordinates. Then the long linear portion of the logarithmic curve becomes a small straight segment very near the operating point, O , and the resulting curve represents the upper half of the characteristic curve, as is shown in Fig. 82. The lower half is simply an image of the upper, and the two together give us the complete function which relates sound pressure to the potential generated in the ear. Now, if the ear were symmetrical, the operating point, where the system would find itself in the absence of any sound, would be at O . The mechanical structure of the ear and possibly the tension of its muscles tend, however, to displace the operating point to some asymmetrical position, such as position A . Then, any sinusoidal force operating about point A will produce a motion having both odd and even harmonic components.

This working picture of the ear, if correct in principle, would mean that for those instances in which the even harmonics de-

cline at high intensities (Figs. 78 and 79), under large sound-pressures, the operating-point tends to move to a more symmetrical position on the characteristic curve. This effect could be

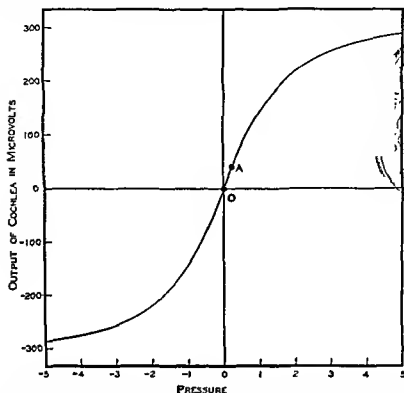


FIG 82 Approximate characteristic curve of the ear. The curve relates the electric potential of the cochlear microphonics (ordinate) to the applied sound pressure in dynes per square centimeter. Thus when the pressure varies sinusoidally about the zero value, the instantaneous voltage in the cochlea may be read from the curve and the resulting wave form determined. Factors such as tension on the muscles of the middle ear may shift the operating point (point corresponding to zero pressure and zero voltage) from *O* to some other point such as *A*. With the operating point at *A*, both odd and even harmonics are present in the output. (Stevens and Newman, 3)

achieved in either of two ways. Either the operating-point could move to a new position on a fixed characteristic curve, or else the curve itself could undergo alteration at large amplitudes. The ear is a very complex structure and as yet we have no means of telling precisely what determines the form of its characteristic curve.

Nevertheless, the effectiveness of the middle-ear muscles in changing the proportion of even harmonics argues that the curvature in Fig 82 depicts a property of the middle ear. On the other hand, the middle and inner ears constitute a closely coupled mechanical system, so that it is not impossible to conceive of the harmonics as originating in the inner ear itself (Bekesy, 17). Certain it is that persons whose eardrums and ossicles are missing from the middle ear experience distortion (Lewis and Reger), but this fact is to be expected, and it does not argue that, in the normal case, the middle ear is not responsible for whatever distortion we hear. Furthermore, in any discussion of the locus of auditory distortion, we should remember that the question is not whether any particular part of the system is nonlinear (it *must* be at large enough amplitudes), but the question is rather which part of the system is most nonlinear, so that its limits of linearity are the first ones reached when the amplitude is increased. It is this part of the system which will determine the form of the characteristic curve, and it is quite possible that different parts of the system perform this function at different intensity levels.

Independent support for the notion that distortion might be blamed upon the middle ear comes from a recent study of the exact mechanical motion of the auditory ossicles (Stuhlman). Beginning with a series of very careful measurements of the dimensions and relative positions of the ossicles Stuhlman constructed a scale model of the middle ear, so that he could study its rather complicated motions. Within the limitations set by the model in simulating the correct suspension and articulation of the ossicles, the experimental evidence showed that a simple sinusoidal motion, impressed at the eardrum, is transmitted to the oval window only after having undergone both asymmetrical and nonlinear distortion. No distortion is introduced at small amplitudes. From his observations, Stuhlman was able to plot the characteristic curve for the ossicles (see Fig 107, p 258). This curve, with its sigmoid form and its asymmetrical operating point, is obviously similar to that in Fig 82.

COMBINATION TONES

Simultaneous stimulation of the ear by two pure tones produces an electric potential, out of which not only the several harmonics of these two tones but also the sum and difference-tones representing combinations of these harmonics can be analyzed (Newman, Stevens, and Davis). The presence of these tones is a necessary consequence of a characteristic curve like that in Fig 82. The procedure here was identical with that used to investigate the aural harmonics: the electrical output of the cochlea of an animal was analyzed by means of a wave analyzer. This method shows clearly that two pure tones, led simultaneously to the ear, produce in the cochlea all the combination tones that can be easily detected by the method of 'best beats' and a great many more besides.

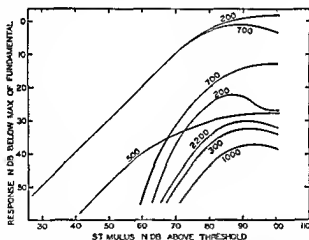


FIG 83 The lower-order difference tones present in the cochlear microphonics when the ear of a cat is stimulated by two pure tones of 700 and 1200 cycles. Abscissa values represent the intensity of the two stimuli in decibels above the average human threshold. The ordinate scale is in decibels below the maximal average value of the two fundamentals. (Newman, Stevens, and Davis.)

Typical behavior of the combination tones resulting from two primary frequencies (700 and 1200 cycles) at various intensities is shown in Figs 83 and 84. These curves are essentially representative of the usual course of the combination tones, but

any particular curve is subject to considerable variability in different experiments. Figure 83 represents the difference tones, and Fig 84 the summation tones. In general, the difference tones are larger than the summation tones of corresponding order. (The *order* of a combination tone is here defined as the number of the highest harmonic entering the combination.) Thus, the first-order difference tone ($500 = 1200 - 700$) is larger than the first-order summation tone ($1900 = 1200 + 700$), although both these tones appear at rather low levels of the fundamental tones and follow functions very similar to

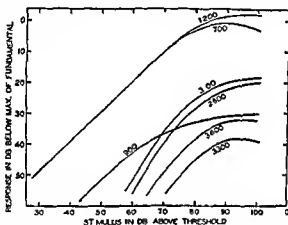


FIG 84 The lower-order summation tones (Similar to Fig 83) (Newman, Stevens, and Davis)

one another. The second-order difference tone ($1700 = 2 \times 1200 - 700$) consistently reaches the largest value of all combination tones. Its complement ($200 = 2 \times 700 - 1200$) is not so large and tends to decline at high intensities. Among the summation tones, one of them ($3100 = 2 \times 1200 + 700$) reaches the largest value, but does not greatly exceed its complement ($2600 = 2 \times 700 + 1200$).

Although the combination tones represented in Figs 83 and 84 include the largest present in the ear, there are many others, including some that surpass occasionally the smaller ones in the figures. A thorough exploration with a wave analyzer (Newman, Stevens, and Davis) of the frequency range 100 to

8000 cycles yielded a grand total of 66 different tones present in the cochlear response of a cat stimulated by 700 and 1200 cycles at 90 db above threshold. If we let L represent the lower tone, 700 cycles, and U the upper tone, 1200 cycles, Table IV gives the magnitude of the tones corresponding to various combinations of U and L taken singly and together. It will be noted that there are in this table as many as 3 tones of the seventh order and 10 tones of the sixth order. The only tones below 6000 cycles involving combinations of the sixth order or less which were not found were $600 = 4U - 6L$ or $6L - 3U$, $1100 = 5L - 2U$, $2500 = 5U - 5L$, and $5800 = 6U - 2L$. The absence of these 4 combination tones may be due simply to their failure to reach the arbitrary criterion of 0.1 per cent of the fundamental.

The astonishing number of combination tones present in the ear, when the external stimulus is a single pair of pure tones, shows us how complex the spectrum of a sound becomes in the process of transmission to the inner ear. Except at low sensation levels, the spectrum in the inner ear is vastly more complex than in the outer ear. Imagine, then, the degree of complexity, within the cochlea, of an orchestral strain composed itself of many component frequencies.

COMBINATION TONES FROM SUPER AUDIBLE FREQUENCIES

It has been reasoned that, since the nonlinearity of the ear allows us to hear a difference tone when two tones are sounded, we should be able to detect the presence of two super audible frequencies by reason of the difference tone which they would produce. Thus, if tones of 25,000 and 26,000 cycles were presented together, we might hear a 1000-cycle difference tone, even though the two high frequencies are separately inaudible. Such, however, is apparently not the case. Recent improvements in high frequency generating devices (Pierce) have made it possible to produce super audible sound waves at very high intensities. Nevertheless, attempts to produce difference tones in the ear by means of these high frequencies have failed com-

pletely. Such a failure is not surprising in view of the fact that the response of the ear is linear for small amplitudes of motion. The over all mechanical tuning of the ear is such that its motion is very slight when being driven at a high frequency—much too slight, apparently, for distortion to appear when available intensities of super audible tones are employed.

On the other hand, when a particular ear is suffering from what we call high tone deafness, tones which are separately inaudible may produce a difference tone when presented together. Thus, in an ear which was unresponsive to tones above 6000 cycles, it was found possible to produce an audible difference tone of 1000 cycles by stimulating the ear with tones of 7000 and 8000 cycles. These stimulating tones were sufficiently intense and low enough in frequency to force the ear beyond its limits of linearity and thereby produce a difference tone. The mere fact that the ear could not hear the two primary tones had no effect on this process of distortion, for the high tone deafness was probably due, in this instance, to a deficiency in the neural rather than in the mechanical mechanism of the ear.

THE THRESHOLD FOR DISTORTION

In the electrical recording and transmission of speech and music, it is the aim of the engineer to design equipment that will not introduce audible distortion. The fact that the ear itself generates harmonics and combination tones affects, however, the amount of objective distortion which can be tolerated in acoustical instruments. A simple method of measuring the audibility of distortion in a tone is to determine the amount of second harmonic which must be mixed with a pure tone in order to produce a just noticeable effect. An experiment in which the sensation level of a 740-cycle tone that was just detectable by its audible effect on a tone of 370 cycles gave the results shown in Fig. 85 (Newman, Stevens and Davis).

TABLE IV

Harmonics and combination tones present in the ear of a cat when pure tones of 700 and 1200 cycles are introduced simultaneously at 90 db above threshold. The magnitude of the response at each frequency is expressed as a percentage of the response of the two fundamentals.

Frequency	Response (%)	Combination	Frequency	Response (%)	Combination
100	2.0	3U - 5L	3700	1.1	6U - 5L
200	7.9	2L - U	3800	2.2	2U + 2L
300	3.7	2U - 3L	3900	.84	5U - 3L
400	.58	4L - 2U	4000	.47	4L + U
500	4.0	U - L	4100	1.4	4U - L
700	100.0	L	4200	.60	6L
800	3.3	3U - 4L	4300	1.0	3U + L
900	1.0	3L - U	4400	.42	6U - 4L
1000	1.3	2U - 2L	4500	2.3	3L + 2U
1200	100.0	U	4600	1.0	5U - 2L
1300	1.8	4U - 5L	4700	.42	5L + U
1400	3.1	2L	4800	.32	4U
1500	1.3	3U - 3L	4900	.33	7L
1600	.16	4L - U	5000	2.7	3U + 2L
1700	18.0	2U - L	5100	1.4	6U - 3L
1800	.83	5U - 6L	5200	.45	4L + 2U
1900	3.2	U + L	5300	.20	5U - L
2000	.58	4U - 4L	5400	.33	6L + U
2100	1.1	3L	5500	.38	4U + L
2200	3.2	3U - 2L	5600	.67	7U - 4L
2300	.17	5L - U	5700	.97	3U + 3L
2400	3.0	2U	5900	.33	5L + 2U
2600	8.0	2L + U	6000	.10	5U
2700	3.5	4U - 3L	6100	.28	7L + U
2800	2.0	4L	6200	.45	4U + 2L
2900	2.5	3U - L	6400	.77	4L + 3U
3000	.20	6U - 6L	6500	.33	6U - L
3100	10.0	2U + L	6600	.12	6L + 2U
3200	1.3	5U - 4L	6700	.25	5U + L
3300	1.2	3L + U	6900	.67	4U + 3L
3400	1.3	4U - 2L	7100	.10	5L + 3U
3500	.20	5L	7200	.15	6U
3600	1.8	3U	7600	.30	4L + 4U

The graph shows that at low sensation levels the second harmonic introduced distortion almost at its absolute threshold value. Hence, if masking is defined as a raising of the threshold, it is apparent that masking of the added harmonic is negligible below a sensation level of 40 or 50 db. From 50 to 80 db, however, the amount of harmonic necessary for an audible change increases rapidly, first in absolute magnitude, and later in relative magnitude as well, but above 80 db the curves for the two observers flatten out significantly.

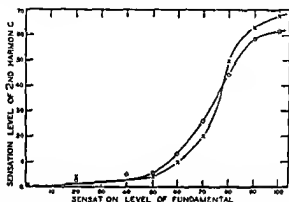


FIG. 85 The sensation level of the second harmonic, generated externally to the ear, which is just detectable when mixed with the fundamental (370 cycles) at various sensation levels. Each curve is for a single human observer (Newman Stevens and Davis).

The qualitative character of the audible change produced by adding this harmonic was different at the various sensation levels of the fundamental. At low levels the harmonic was usually heard as a separate tone. In the middle region it was heard as a sharpening or brightening of the timbre of the tone, whereas at high levels the changes were so complex and so dependent upon differences of phase that any generalization about their character would be misleading.

The relation of this threshold for distortion to the aurally generated harmonics is reasonably clear. Masking of the externally generated harmonic arises at about the level at which the aural harmonic begins first to appear. At somewhat higher

levels, it is plain that various forms of interference between the two types of harmonics are responsible for a wide variety of subjective effects. It is also in this region that phase relations between the fundamental and the externally generated harmonic become important. Finally, the flattening-off at the tops of the curves is reminiscent of the form of the functions describing the aural harmonics (Fig 78). The course of the threshold for distortion and its parallel to the aural harmonic thus suggest that the threshold for distortion stops increasing at the point where the aural harmonic ceases to grow.

THE EFFECT OF PHASE RELATIONS AMONG HARMONICS

Not only does the phase of a harmonic that is present in the stimulus have an effect upon the threshold for distortion, but it may also influence the subjective effects of a complex tone. This statement is contrary to the usual assertion that, under Ohm's auditory law, the ear tends to analyze the components of a complex sound regardless of their phase relations. Those experiments in which an auxiliary tone was made to beat with an aural harmonic prove definitely that the phase relations among the harmonic components of a stimulus are detectable, for otherwise these beats could not occur. A harmonic in the stimulus may reinforce or cancel an aural harmonic. Under the method of 'best beats' we perceive an alternate reinforcement and cancellation due to a constantly changing phase between the auxiliary tone and the aural harmonic. When, however, the auxiliary tone is identical in frequency with the aural harmonic, no beats are heard, but it can be shown that the auditory experience which occurs nevertheless depends upon the phase-relation between the auxiliary tone and the aural harmonic.

There is one phase relation between these two tones which gives a definite increase in loudness, both of the harmonic and of the total experience, there is another which decreases the loudness. In other words, a given tone, plus another tone of exactly twice the frequency, may sound either louder or less loud than the fundamental alone. Furthermore, the phase

yielding maximal loudness differs from that giving minimal loudness by 180° .

The effects of adding various amounts of second harmonic in three different phase relations are shown in Fig. 86. To a tone of 108 cycles, at an intensity-level of 104 db, was added a 216-cycle tone in such phase-relations as to give (1) maximal loudness, (2) minimal loudness, and (3) intermediate loudness. Curve *A* shows how the experienced loudness changes when the added harmonic is set to give minimal loudness. In this

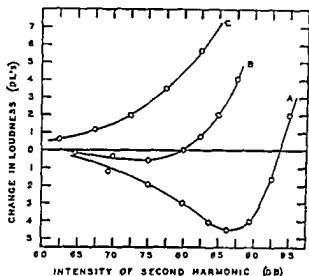


FIG 86 Showing how the total loudness changes when a 216-cycle tone (second harmonic) is added to a 108-cycle tone in three different phase-relations. The change in loudness is measured in terms of just perceptible steps (DL's). Curve *A* is for the phase-relation giving minimal increase in loudness, curve *B* is for intermediate and curve *C* is for maximal increase in loudness. The tone represented by curve *A* is 180° out of phase with the tone represented by curve *C*. (After Chapin and Firestone)

case, the 216-cycle tone is opposite in phase to the second aural harmonic and cancellation occurs. Consequently, as the intensity of this added harmonic is increased, the loudness declines, until finally the second aural harmonic is completely canceled. Thereafter, the loudness increases with added intensity of the harmonic. Presumably, then, where curve *A* reaches a mini-

mum, the added harmonic is equal in magnitude and opposite in phase to the aural harmonic, and the occurrence of this minimum at about 87 db is consistent with the curves of Fig 76. Curve *C* represents the situation where the added harmonic is 180° out of phase with the harmonic used to obtain curve *A*, and is presumably in phase with the aural harmonic. Hence, loudness always increases when the intensity of this added harmonic is raised. Curve *B* shows how an intermediate phase produces an intermediate effect.

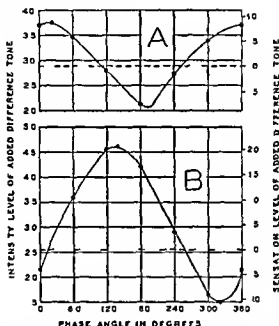


FIG 87 Showing how intense an added tone, equal to the difference between two other tones must be in order to produce a detectable increase in the loudness of the aural difference tone. The phase of the added tone is shown by the abscissa. At certain phases, the added tone is below the threshold of audibility for that frequency, as shown by its negative sensation level. Plots *A* and *B* are for two different observers. (After Lewis and Larsen.)

Not only does a change of phase alter the loudness of a harmonic, and of the total experience, but it produces noticeable differences in quality, provided the fundamental is a low tone of 100 cycles (Trimmer and Firestone). The phase relation giving minimal loudness is characterized by smoothness, whereas the opposite phase, which leads to maximal loudness, carries

with it a rough or dissonant element. The phase giving minimal roughness was found to be almost the same as that giving minimal loudness, although considerable variability occurred among different observers.

Just as the aural harmonics can be interfered with by a tone of the proper frequency and phase, so also can we investigate combination tones by adding to the stimulus frequencies equal to the tones generated in the ear. Lewis and Larsen worked with a difference tone of 130 cycles created by the two frequencies, 390 and 520 cycles, at an intensity level of 70 db. They measured the intensity of a 130-cycle tone which, when added to the combination in various phase relations, was just sufficient to make the difference tone sound noticeably louder. The results for two observers are shown in Fig. 87, where we see that much less energy is needed at certain phases than at others. On the assumption that, in order to make the difference tone just noticeably louder, the least energy is required when the added tone is exactly in phase with the difference tone, we may determine this phase relation from the lowest points on the curves of Fig. 87. Apparently the difference tone has a phase of 200° in the ear of observer *A* and of 320° in the ear of observer *B*.

THE STABILITY OF THE CHARACTERISTIC CURVE

Now, we should like, of course, to be able to explain all the results of the experiments considered in this chapter in terms of the approximate characteristic curve drawn in Fig. 82. The problem would be greatly simplified if we could assume that this curve portrays the characteristics of a typical ear under all conditions of stimulation. However, before we can feel secure in this assumption, certain difficulties must be explained. Our limited experimental evidence indicates that the relative phases of the aural harmonics and combination tones are disconcertingly different from ear to ear. Likewise, the magnitudes of these tones show considerable variation among different observers. Why distortion in different ears should exhibit such lack of uniformity is not clear at present.

Another complication, waiting to be explained, is the fact that the size of the aural harmonics, as measured directly in the ear of a cat, is greatly altered by the presence of another tone (Newman, Stevens, and Davis). Thus, the third aural harmonic of a 700-cycle stimulus was found to be reduced by about 20 db when a 1200-cycle tone was sounded simultaneously. Not only were the aural harmonics reduced, but they changed size very irregularly as a function of intensity. A fixed characteristic curve would not by itself account for this effect. The solution of these difficulties waits for further experimental evidence.

CHAPTER 8

AUDITORY MASKING FATIGUE AND PERSISTENCE

THERE are, in general, two conditions under which a normally effective auditory stimulus may fail to arouse a sensation. One is when it is accompanied by another sound which obliterates or masks it, the other is when it is preceded by a sound which leaves the organism unresponsive or fatigued.

MASKING

One tone is said to produce masking when it raises the threshold of a second tone. We have already seen how it is possible to use data from experiments on masking to calculate the loudness of certain sounds (Chapter 4). Here we shall examine other problems connected with auditory masking.

The measure of masking is the number of decibels that the threshold of the masked sound is elevated in consequence of the presence of the masking sound. The simplest method of measuring masking is to turn on the masking sound and then gradually to increase the intensity of the masked sound until its presence is just detectable. The difference between this value of the intensity of the masked sound and its threshold intensity when no masking sound is present is the masking value. The temporal relations in the presentation of the two sounds and the number of observations made with them are, of course, important variables in an experiment on masking (Wever and Truman).

Wegel and Lane made an extensive study of the masking effects of pure tones and found that these effects vary greatly with the frequency and intensive relations of the tones. Figure 88 shows the amount by which tones of various frequencies are masked by the presence of another tone at different sensation levels. Each plot is for a masking tone of different frequency

F_p , as indicated, whose sensation-level is shown by the abscissa. The ordinates give the change in threshold—the masking—

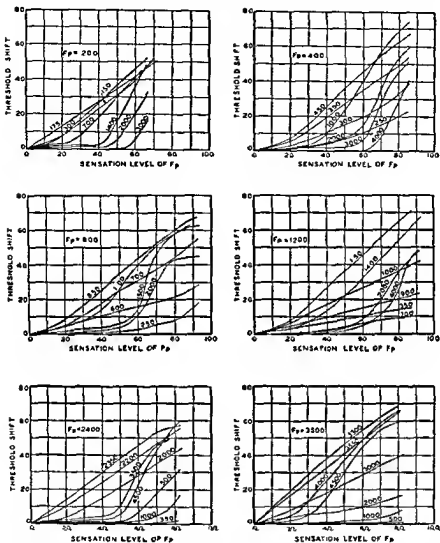


FIG 88. Curves showing the ability of different frequencies F_p (indicated on each plot) to mask other frequencies (indicated by the numbers attached to the curves). The sensation level of the masking tone is shown by the abscissa, and the elevation in the threshold of the masked tone by the ordinate. (After Wegel and Lane)

suffered by the frequencies indicated by the separate curves. From these plots, certain general facts are evident. A tone of

a frequency much below the masking tone is not perceptibly masked when the intensity of the masking tone is low, and even when the masking tone is loud the effect on a tone of lower frequency is but slight. A tone of much higher frequency than the masking tone is not perceptibly masked by a weak masking tone, but, as the intensity of the masking tone is increased beyond a certain value, the degree of masking grows rapidly. In other words, a loud tone masks tones higher than itself more easily than it masks lower tones. In general, masking is greater when the tones lie close together in frequency. In this event, the curves tend to approach lines with 45° slopes which intercept the axis of the abscissae at a sensation level of the masking tone equal to about 20 db.

When the tones are close enough together in frequency to beat, they do not give rise to masking in the same sense as when farther apart. Measurements of masking then represent the minimal perceptual fluctuation of the beating tone. In the special instance when two such tones are so faint as to be separately just inaudible, they will, when introduced into the ear together, beat in such a way as to be alternately audible and inaudible. Hence, in this case, we actually obtain a reinforcement, i.e., a negative value of masking.

The sudden increase in the slopes of those curves in Fig. 88, for which the masked frequency is higher than the masking frequency, is associated with the appearance of aural harmonics. This effect is illustrated in Fig. 89, which represents the masking due to a 1200-cycle tone at a sensation level of 80 db. The solid curve resembles such a curve as we might expect if three masking frequencies, 1200, 2400, and 3600 cycles were present, with relative magnitudes of 40, 4, 1. These frequencies were not, however, present in the stimulus—they were introduced by distortion due to the nonlinear transmission of the ear. Wegel and Lane determined the magnitude of these harmonics by measuring the intensity at which another tone, differing a few cycles from the harmonic, produced the most prominent beats when sounded simultaneously.

The character of the sensation caused by two tones, acting

simultaneously on the ear, varies considerably with the relative frequency and intensity of the tones, because the same non linearity which introduces harmonics at high intensities gives

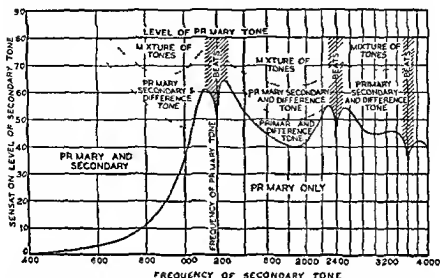


FIG 89 The various sensations produced by two pure tones one (the primary) at 1200 cycles and 80 db above threshold the other at a frequency and sensation level as shown by the coordinates (After Wegel and Lane)

rise to combination tones when both tones are sufficiently loud. Thus Fig 89 represents the sensations obtained when a 1200-cycle tone, at 80 db above threshold, is combined with different secondary frequencies whose sensation levels are indicated on the ordinate of the graph. The various areas represent ranges of frequency and intensity of the secondary tone in which combination tones of various kinds, as indicated, appear. When any secondary tone of a frequency below about 1000 cycles is raised in intensity from a sub audible value to a point at which it is just detectable, it is first heard as a separate tone along with the primary tone. In the lower part of this frequency range, the intensity of the secondary tone may be increased to very large values and the tone still will be perceived independently of the primary. When, however, the intensity of the secondary tone is increased to a point indicated by the dotted line, the difference tone is distinguishable and increases gradually in

relative intensity as the area above this line is crossed. At very high intensities, in this region, a complex mixture of tones is heard. On the other hand, when a higher secondary tone, 1900 cycles for example, is introduced in the same way, its presence is first detected by the appearance of a difference tone, and the secondary itself is not heard. Then, as the intensity is further increased, the secondary tone becomes audible along with the difference tone, and, with still further increase in intensity, the mixture of tones becomes more and more complex. All these effects are what might readily be predicted from a study of the facts presented in the previous chapter.

A special interest attaches to the masking effects of very low tones, because of the persistent uncertainty that faces us regarding the mechanism of pitch perception in this region. Here,

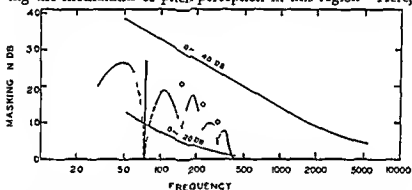


FIG. 90. The masking produced by low tones. The masking produced by the 10-cycle tone at 20 and 40 db above threshold was measured by Bekésy (22). The vertical line shows the sensation level of a 75-cycle tone employed by Fletcher (2) to mask other frequencies, as indicated along the abscissa.

however, our interest is more abundant than our data. Bekésy (22) presents us with results obtained by measuring the elevation in the threshold of a wide range of tones listened to in the presence of a 10-cycle tone at two sensation levels—20 and 40 db. This very low frequency, at 40 db above threshold, masks a major part of the audible frequency range, as shown in Fig. 90. Even at 20 db above threshold its effects are rather wide spread. One other record of masking by a low frequency—75 cycles—comes to us from Fletcher (2). His is the middle

curve of Fig 90 The dotted portions are the regions in which beats appear, and the circles above the curve show the magnitudes of the several harmonics of the 75-cycle tone The general course of the curves for 10 and for 75 cycles is clearly similar, although the masking due to 75 cycles shows some evidence of decreasing for frequencies lower than this tone—an important fact, if finally established

THE MASKING OF SOUND IMPULSES

It is manifestly impossible to mask a steady tone by means of a short impulse of sound, for the tone would be heard before and after the impulse The reverse experiment can be carried out however and Békésy (15) has obtained the pair of curves in Fig 91 showing how loud a tone must be in order to mask

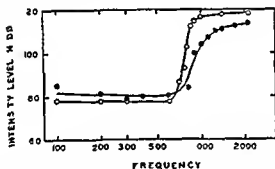


Fig 91 The intensity level at which various tones are just able to mask a click whose loudness-level is 40 db (After Békésy 15)

a click whose loudness level is 40 db Each of these curves is for a single observer As we might well expect, the tone does not completely suppress the click unless its loudness-level is considerably above that of the click—30 db at the least Tones below about 700 cycles are distinctly more effective in masking impulses than are tones of higher frequency Although this last conclusion is supported by Békésy's results, we may be critical of its generality, for we have already seen how varied can be the effects of impulses of different wave forms (see p 157) Perhaps Fig 91 would look different for other types of short sounds

MASKING WITH TONES IN OPPOSITE EARS

Crucial to any quest for the origin of the masking effect is a knowledge of what happens when we put the masking tone in one ear and the tone to be masked in the other. Figure 92 supplies this information. A tone of 1200 cycles was used to mask other tones whose frequencies are indicated on the plots. When both tones were led to the same ear, the masking was as shown by the dotted lines, but, when the two tones stimulated opposite ears, the masking fell to the values indicated by the solid curves. The solid and the dotted curves are generally

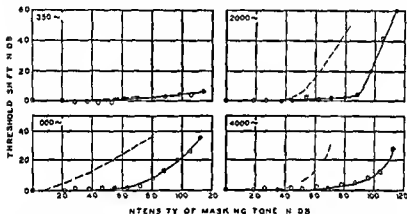


FIG. 92 Showing to what extent a tone of 1200 cycles at various intensities is able to mask a tone in the opposite ear (solid curves). The dotted curves show the masking when both tones are led to the same ear. (After Wegel and Lane.)

similar in form, but the solid curve is displaced 40 to 60 db to the right along the horizontal axis. In short, the masking tone must be raised 40 to 60 db in intensity before the masking in opposite ears equals the masking in one ear alone. The curves of Fig. 92 may be explained if we assume that there are two kinds of masking, central and peripheral. (Wegel and Lane.) Central masking is relatively small, but is probably always present. By contrast, peripheral masking is relatively large, but is present only when the two tones stimulate overlapping areas on the basilar membrane.

A larger amount of masking occurs, even when the tones

are in opposite ears, whenever the intensity of the masking tone is great enough. Note how sharply the curves bend upwards in the region of 60 to 80 db. This behavior is understandable on the assumption that stimulation at high levels causes some sound to be conducted through the head to the opposite ear, where it establishes peripheral masking. In keeping with this notion, we must assume, then, that the attenuation through the head from one ear to the other is of the same order of magnitude as the horizontal displacement between the dotted and the solid curves of Fig. 92 (see Chapter 11).

There is still further evidence that when a tone is introduced into one ear by a telephone receiver, the opposite ear is excited to some lesser degree. People very deaf in one ear are able to hear with the receiver on the deaf ear, provided the intensity is raised 40 to 60 db above that required with the receiver on the normal ear. Hearing, under these conditions, is improved by plugging the good ear with the finger—a simple test, which shows that the sound reaching the good ear gets there by bone conduction.

RELATION BETWEEN MASKING AND EXCITATION

The curve, or audiogram, depicting the course of the auditory threshold in the presence of a masking sound, may be interpreted as a picture of the pattern of excitation within the cochlea, for which the masking sound is responsible. Thus, in Fig. 89, where we find that the presence of a 1200-cycle tone at 80 db above threshold raises the threshold for a 2000-cycle tone by about 40 db, we have evidence that the 1200-cycle tone does something to affect the sensitivity of that part of the basilar membrane which normally responds to a frequency of 2000 cycles. If a single tone were able to confine its effects to a very restricted area of the membrane, it would mask other tones only slightly—and this masking would be central in origin—but owing to the large amount of damping in the ear, a single frequency stimulates a wide area. To this spread there is added, at great intensities, the effects of the aural harmonics, with the

result that a loud tone may make its presence felt, to some extent, throughout the entire cochlea

As an example of what the patterns of excitation in the cochlea are like in the event of stimulation by a single tone of 1000 cycles, at several intensities, consider Fig 93 These curves were adapted from data on the masking effects of a 1000-cycle tone (Fletcher, 2) The humps in the upper curves represent the aural harmonics, and they appear at distances along the ab-

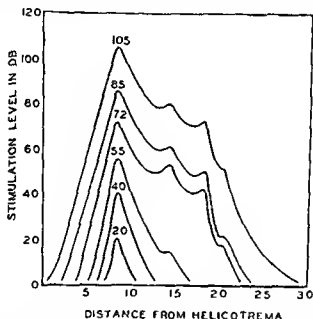


FIG 93 The patterns of stimulation on the basilar membrane due to a tone of 1000 cycles as determined from data on masking The parameter here is the intensity level of the 1000-cycle tone

scissa corresponding to their proper locus within the cochlea, as outlined in Chapters 3 and 15

We have said that the curves of Fig 93 correspond to the actual patterns of excitation, or stimulation, on the basilar membrane This statement is true enough, provided we define excitation in terms of masking Such a procedure is safe, but its safety does not compensate for the fact that it still leaves us vague as to just what features of the activity of the auditory mechanism

will determine whether or not a tone will be masked. There are alternative possibilities. Wegel and Lane suggest that, in order that a tone be heard above a masking tone, its amplitude of motion at its proper locus on the basilar membrane must equal the amplitude already existing at that locus as a result of the masking tone. Then the curves of Fig. 93 would represent the relative amplitudes of vibration of the basilar membrane at different positions. Before proceeding with this interpretation, it is important to note that the ordinate of Fig. 93 is logarithmic. Changed to a linear ordinate, the peaks of the curves would be much more salient.

Another possibility is that masking bears no simple relation to the mechanical motion of the basilar membrane, but is a function of the level of excitation in the fibers of the auditory nerve. In this case, the parts of the curves of Fig. 93 lying between the harmonic peaks would represent the magnitude of certain neural events. Although the quantitative relations between amplitude and nerve potentials are yet to be explored, the characteristics of the nervous mechanisms involved in hearing certainly account for some types of masking (see p. 409).

FATIGUE

Auditory fatigue is an interesting phenomenon, more because of its absence than because of its presence. It is surprising that the ear, assailed as it is both day and night by sounds and noises of all sorts, suffers so little decrement in acuity. No flap or lid enables us to protect our ears from unwanted disturbances, and we must even leave them open when we sleep. Happily we learn to disregard the great bulk of the sounds we hear, at the same time preserving a selective attention for what we consider significant. Even in sleep we may learn to disregard the roar of traffic from the street, but waken at the faint sound of some one stirring in the room. Not that excessive unwanted noise is without ill effects upon the organism, but, as far as the ear itself is concerned, the din of modern life leaves us little the worse for it.

It is true that extreme sound pressures may shatter the audi-

tory mechanism by producing actual lesions that lead to permanent loss of hearing (see Chapter 15), but this does not constitute fatigue. By fatigue we mean a temporary loss of auditory sensitivity due to previous auditory stimulation. Obviously then, the straightforward method of measuring fatigue is to determine a subject's sensitivity before and after he has been stimulated by the fatiguing sound. Three of the most common measures of fatigue have been (1) the change in the absolute threshold of a sound, (2) the change in the apparent loudness of a sound, and (3) the change in the apparent position of a binaurally localized source of sound (cf. Banister for recent review).

A variety of studies, using these methods, have demonstrated auditory fatigue. But instead of disclosing a precise and easily measurable phenomenon, these studies show auditory fatigue to be elusive and variable, and the reader finds a considerable lack of agreement in the sporadic literature on the subject. There are no charts showing quantitatively the amount and duration of losses, due to previous stimulation, for a wide range of frequencies and intensities. We must content ourselves with a few generalizations to which the exceptions are all too numerous.

Previous stimulation causes an elevation of the auditory threshold, but the effect is generally short lived—a matter of a few seconds to a few minutes. Whether the fatigue will last seconds or minutes has been said to depend on the frequency of the stimulating tone (Bronstein and Churilova). Thus the time necessary for the threshold to return to normal after the ear had been exposed for 2 min to tones at a loudness level of 94 db increased from 20 sec to 6 min as the frequency of the fatiguing tone was raised from 100 to 4000 cycles. But differences among individuals are large as regards the duration of fatigue.

The greatest amount of fatigue occurs at the frequency of the stimulating tone, but for low tones the effects of fatigue—when any—may spread to frequencies fairly far removed. Previous stimulation also causes a loss in the loudness of subsequent tones, and here again there is evidence that the loss is greatest

at or near the fatiguing frequency. This type of evidence, so far as it goes, suggests that the pattern of fatigue on the basilar membrane presents the same sort of picture as that disclosed by the masking curves of Fig. 93.

An interesting consequence of such a pattern of fatigue is reported by Békésy (3) who found that, as a result of exposure to an 800-cycle tone, the pitch of tones slightly removed from 800 cycles was raised or lowered, depending upon whether the tone was above or below 800 cycles in frequency. This change in pitch was greatest at 500 and at 1200 cycles, and amounted to about 7 per cent. Békésy's explanation is to the effect that the 1200-cycle tone finds the pattern of fatigue along the basilar membrane to be greater just below than just above the region which resonates to 1200 cycles. Hence, the pattern of excitation due to the 1200-cycle tone becomes skewed in such a way that its maximum is shifted along the membrane toward the oval window, and the result is an elevation of the perceived pitch. An analogous, but opposite, effect occurs at 500 cycles.

A novel aspect of the problem of auditory fatigue comes to light in the work of Rawdon Smith (2) and appears to explain why so many careful and well planned experiments have led to contradictions. In the first place, he found that, when the fatiguing stimulus falls on one ear, the opposite ear suffers a decrement in sensitivity—a decrement which is not limited to the fatiguing frequency alone. Hence, some of the effects which we class as auditory fatigue appear to originate centrally.

Now, when the factors causing a change in an organism's normal response to a stimulus are conditioned upon the state of the central nervous system, we are not surprised when we find increased variability. Central inhibition is a labile phenomenon. Consequently, both the variability and the binaural nature of auditory fatigue can be accounted for, if we assume that the loss in sensitivity is due to the intervention of cortical factors. The phenomenon would partake, then, less of the nature of sensory fatigue than of the nature of *inhibition*, and the well known phenomenon of *disinhibition* (Pavlov's *inhibition of inhibition*) would be likely to appear. Rawdon-Smith

looked for this effect and found it by giving the observer an unexpected, but innocuous, stimulus, such as momentary darkness in the sound proof room. His threshold, which had been tested immediately before the unexpected stimulus, was retested at once, and was found to have moved toward the normal unfatigued level. Thereafter, the sensitivity declined again, but could be restored by repeating the unexpected stimulus.

The phenomenon of auditory fatigue appears, then, to be complicated by some type of central inhibition, which makes it hard to discover, by psychophysical experiment, the actual loss of sensitivity within the sense-organ due to previous stimulation. Perhaps we had best turn, for this information, to the more direct observation of the behavior of the ear, as it is revealed in the electrical output of the cochlea (see Chapters 13 and 14).

SENSITIZATION DUE TO STIMULATION

Before leaving the problem of auditory fatigue, we should consider an apparently opposite effect which arises under conditions which would be expected to produce fatigue. A series of studies by Bronstein shows that after exposure to a loud tone the auditory threshold not only returns to normal, but also, often, it falls below normal for a period of time. This increased sensitivity, which may amount to 10 or 15 db, extends to frequencies other than that of the stimulating tone. As with fatigue, there is some sensitization of the opposite ear, when only one ear has been stimulated. This, and other features of the phenomenon, suggest that sensitization and fatigue are both due, in part, to cortical factors.

THE PERSISTENCE OF SENSATION

Closely allied to the problem of the after-effects of sound stimulation is the problem of the duration of the sensation itself. We are all aware that the sensation stops abruptly when a tone is turned off, and in audition, unlike vision, we experience no marked after images. So quickly, in fact, does the effect of an

auditory stimulus die out that the measurement of its rate of decay is a difficult undertaking

The problem has interested many investigators, including Helmholtz, but, unfortunately, much skillful experimenting has been squandered on an effort to determine auditory persistence by a kind of 'flicker technique'. Experimenters have set out to discover how rapidly a tone must be turned on and off before the interruptions are too brief to be noticed, so that fusion occurs. The success of the flicker method in vision is beyond question, but in audition it is a failure. The reason lies in the fact that it is impossible, in a sense, to turn a tone on and off, for when we try to do so we merely introduce additional frequencies into its acoustic spectrum and obtain a more complex sound. (The same result is true, actually, of a visual stimulus, but, as we saw on p. 94, the effects of modulating a light are negligible, compared with the sensitivity of the eye.) The next chapter treats the problem of modulation, and we shall see there that the turning on and off of a tone is essentially a case of amplitude modulation. Consequently, most of the experiments designed to measure the persistence of auditory sensations can best be classified as experiments on modulation, and the results can be explained in terms of the effects of modulation on the frequency spectrum of a sound.

Are there, then, any experiments which can be said to measure persistence? It is quite likely that certain observations by Bekesy (14) can be so classified. He measured the slowest rate of decay of a tone which would give the sensation of a tone ending abruptly. He allowed a tone to die out exponentially over a period of time that was long enough to be clearly detectable and he then proceeded to shorten the time of decay until further shortening gave no noticeable difference. In other words, a rate of decay can be found such that a faster rate makes no difference in the sensation—no difference, that is to say, until the tone ends so abruptly that a click is heard. Presumably, this critical rate of decay is just equal to the rate of decay of the sensation itself, and any more rapid decay in the stimulus is obscured by the fixed rate of decay of the sensation.

Figure 94 gives the values of the critical rates of decay for an 800-cycle tone as a function of sensation level. The ordinate gives the time necessary for the tone to die out to one thousandth of its initial value, i.e., to decline through 60 db.

Now, since Békésy has given us the rate of decay for these tones, and also their initial intensities in decibels above threshold, it is a simple matter to calculate the time which will elapse before they decline to the auditory threshold. From Fig 94 it is clear that the critical rate of decay for the louder tones is

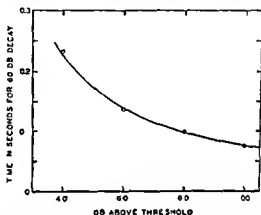


Fig 94 The decay time of an 800-cycle tone which is extinguished at the rate of physiological decay. The abscissa gives the initial sensation level of the 800-cycle tone. (After Békésy, 14)

greater than for the weaker ones. In fact, if we plot the decay of each tone, as a function of time, we obtain the results shown in Fig 95. Here it is apparent that, regardless of the initial intensity, all the tones reach the value of the auditory threshold in approximately the same length of time, namely, 0.14 sec. Consequently, if we accept the argument that these rates of decay are equal to the rate of decay of auditory sensation, we are forced to conclude that, regardless of the intensity of stimulation, a sensation will take very nearly 0.14 sec to die out after stimulation ceases.

Is such a conclusion reasonable? Not if the persistence of sensation is due to continued mechanical vibration of the ear,

nor if it is due to the accumulation of some excitatory neural substance whose concentration depends on the intensity of stimulation, for in both these cases persistence would be longer when the tones are louder. However, if we assume that the central neural elements responsible for auditory sensation behave in a strictly independent fashion, so that added intensity of stimulation serves merely to increase the *number* of elements excited, then the effect due to each element would die out independently, and we should expect to find that intensity makes no difference to persistence. If such is true, we may consider that the time 0.14 sec represents approximately the time of decay of the excitation of a single one of these central elements, and also the time of decay of the total auditory sensation.

It is necessary to assign this phenomenon of persistence to a central mechanism, because no persistence as great as 0.14 sec has been observed in the physiological effects detectable in the cochlea or in the auditory nerve. All that we can really conclude, provided Bekésy's relations can be shown to hold at other frequencies, is that there is not, in audition, the type of summation that builds up an excitatory substance, having a constant rate of decay, in such a manner that higher concentrations occur at higher intensities of stimulation. The exact mechanism underlying a phenomenon of persistence having the characteristics shown in Fig. 95 remains to be determined.

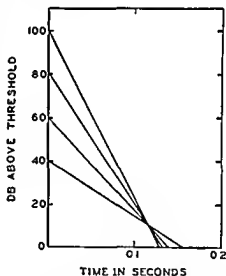


FIG. 95. The decay-curves for an 800-cycle tone beginning at various sensation levels (ordinate) and decaying to threshold. The rate of decay is the critical rate determined by Bekésy (14) and the time to reach threshold is shown on the abscissa by the intersections of the curves with the zero-ordinate.

In auditory experiments, the practical problem often arises as to what should be done about turning tones on and off in such a way as to avoid a click and yet give the impression of instantaneous starting and stopping. Figure 95 shows that the ideal way to turn a tone off is to allow it to decay to threshold intensity over a period of 0.14 sec. Likewise, the ideal build up time for turning a tone on is of the same order of magnitude, although quantitative measurements of this effect appear not to have been made.

CHAPTER 9

MODULATION VIBRATO AND BEATS

WHENEVER a characteristic of a sound wave is varied, the wave is said to be *modulated*. Thus if we change the amplitude, the frequency, or the phase of a sound, we produce amplitude, frequency, or phase modulation. Even when we turn a tone on and off, we are effectively modulating the tone, although in practice, the term *modulation* usually refers to a *periodic* modification of a wave. All three types of modulation may occur singly or together, but our chief concern will be with the effects of amplitude or of frequency modulation occurring alone.

THE NATURE OF MODULATION

First, let us examine the nature of a modulated tone, in order to see just what is the difference between frequency and amplitude modulation. Suppose that we have an audio oscillator producing a pure tone in a loud speaker. We could very easily produce an amplitude modulation by wiggling back and forth the dial controlling the intensity of the tone. Or we could create a frequency modulation by turning the tuning control up and down. An oscillographic record of the resulting sound wave would look quite different in the two cases. Manipulation of the intensity control would give us a wave whose height from crest to trough varies with time, whereas turning the frequency-dial would produce waves which are alternately closer together and farther apart. Suppose, now, that each dial is turned back and forth in a simple periodic fashion, so that the changes produced in the tone are sinusoidal with time. Then we should be producing the simplest form of periodic modulation. We could take an oscillographic record of these two types of modulated waves and analyze them into their Fourier components, in order to discover what steady tones would, when

mixed together, produce the same form of wave. These steady tones make up what we term the *acoustic spectrum* of the wave.

Now, when it is discovered that a modulated wave can be analyzed into a spectrum of steady components, the question arises as to how we are to regard modulated tones. Are they tones which vary continuously in either amplitude or frequency, or are they groups of steady tones? The answer is that they are both—they may be regarded from either point of view, depending upon our purpose. The steady components are actually present in a physical sense, as can be shown by the type of analyzer capable of responding to certain individual frequencies and of excluding others. On the other hand, when all the frequencies in the spectrum of a modulated tone affect simultaneously the same vibrating body, such as a microphone, they force it into a form of vibration whose amplitude or frequency varies continuously with time. In the example we have been considering, the modulated tone was produced by varying continuously a control on an oscillator. We could have produced precisely the same tone by turning on several oscillators, each tuned to a definite frequency, provided the tones from the different oscillators had the proper phase and amplitude relations.

When our purpose is to study the effects of modulated tones upon the ear, it is most profitable, as we shall see, to regard the modulated wave as a spectrum of steady components. The ear, as a frequency analyzer, tends to respond to each component separately. It fails to resolve these components completely one from another, for the ear is an imperfect analyzer, but we can understand its failures once we grasp the nature of its task. Basic to this understanding is a knowledge of the spectrum of a modulated tone.

A direct method of obtaining the component frequencies in a modulated wave is by mathematical calculation (see Appendix I). In the equation for a simple sinusoidal wave, we can substitute, in place of the constant which stands for the amplitude of the wave, a function that varies with time, and solve the equation. We then obtain the frequency and amplitude of all components of the wave whose amplitude is being modu-

lated. An analogous substitution and solution discloses the components generated by frequency modulation. In both cases, we discover that whenever we modulate the frequency or the amplitude of a tone we obtain a complex spectrum consisting of a central component, or band, with side bands distributed symmetrically on either side. These side bands are spaced a distance apart equal, in cycles per second, to the *rate* at which the modulation occurs. Their relative amplitudes are a function of the *range* of the modulation, where range is defined as half the distance between the highest and the lowest frequency or amplitude reached during any part of the modulation. Now, when the amplitude of a tone is modulated sinusoidally, the resulting spectrum contains the central component and only two side bands, one above and one below the frequency of the central component. However, when the frequency is modulated sinusoidally, the number of side bands is theoretically infinite, although, when the range of modulation is small, only those side bands close to the central band have appreciable amplitude. Thus, when the range is numerically less than half the rate, the spectrum consists of only three appreciable components—just as does the spectrum of a wave undergoing amplitude modulation. Furthermore, there is the surprising fact that the three components arising from frequency modulation may be identical in frequency and intensity to those generated by amplitude modulation.

In other words, we find that three different frequencies led simultaneously to the ear may give rise, in one instance, to the sensation of a tone waxing and waning in loudness, and the same three frequencies may, in another instance, produce the impression of a tone whose pitch rises and falls. How, then, are we to explain this effect? Since the components in the two spectra are alike in amplitude and frequency, the only difference possible between them is one of phase. And it is, in fact, just a difference of phase which determines whether the three components will summate to give a frequency modulation or an amplitude modulation.

In order better to illustrate these important relations, let us

choose three components whose frequencies are 6, 8, and 10 cycles, and let the amplitude of the 8-cycle component be 4 times as large as the amplitudes of the two side bands. Then, as shown in Fig 96, we can arrange the phases of these com-

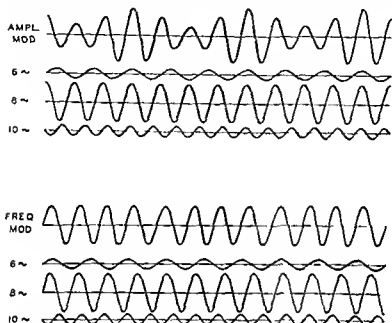


FIG 96 Showing how the same three components 6, 8, and 10 cycles, can be added in different phase relations in order to produce either an amplitude or a frequency modulation

ponents in such a way that the three waves added together give an amplitude modulation. However, if we shift the phase of the central component by 90° we find that the three waves summate to produce a frequency modulation. In Fig 96 each of the modulated waves was obtained by adding algebraically the instantaneous amplitudes of the three waves drawn directly under each. (Actually, in constructing the wave whose frequency is being modulated, other side bands were neglected, but the amplitude of the largest of these amounts to only 3 per cent of the amplitude of the central band.)

These interesting relations between the two types of modu-

lation obtain likewise when the two spectra are more complex, and it is possible, in general, to transform a frequency modulation into an amplitude modulation by readjusting the phases of the components. If there are more than two side bands, however, the amplitude modulation will be nonsinusoidal. At intermediate phases we may obtain a combination of frequency modulation and amplitude modulation. Thus, if we had changed the phase of the center band (Fig. 96) by 45° we should have created just such a hybrid modulation. We find, then, that in specifying the spectrum of a modulated wave, we must state the frequency, the amplitude, and the phase of each component. All three of these variables are specified in the formulas for modulated tones (see Appendix I).

Now, the role of phase turns out to be unexpectedly crucial in these considerations, despite the well accepted doctrine that the ear does not take account of phase relations. We have already encountered in Chapter 7 instances in which changes in the phase relations of harmonic components produced noticeable effects, but here we have even more dramatic evidence that the ear may be extremely sensitive to the relative phases of the components of a sound. Consequently, before proceeding to a consideration of specific experiments involving modulation, it may be profitable to inquire into the behavior of the ear under the impact of a modulated tone.

Since any type of modulated wave can be analyzed into a spectrum containing several steady components, the ear would, if its tuning were sufficiently sharp, hear all the components independently and simultaneously, just as it hears at once the flute and the cello in an orchestra. Then, when the tuning dial of an oscillator is turned back and forth, instead of hearing a pitch which rises and falls, we should hear only a group of steady tones spaced a certain distance apart. Even though the tuning dial were moved continuously, so that, to all appearances, the change in frequency is likewise continuous, there would be certain frequencies which we should hear and intermediate frequencies which we should not hear¹. Such is the nature of frequency modulation—a continuous change in frequency pro-

duces a discontinuous spectrum. Nothing, perhaps, is more contrary to intuition than that we should be able to change the frequency of an oscillator continuously between two limits without producing all intermediate frequencies, but that is precisely what we do when we generate a sinusoidal frequency modulation. And if the ear were a better analyzer it would tell us so.

As it is, the ear does not completely resolve the components of the spectrum, and we hear a pitch which follows the movements of our tuning dial, provided they are not too rapid. The explanation of this fact is apparent because the ear is not very sharply tuned, each of the components stimulates a rather wide area on the basilar membrane, and these areas of disturbance overlap to some extent. It happens, in a frequency modulation, that the components at one end of the spectrum are in such a phase relation that, at one time during the modulating cycle, these components all reinforce each other and cause the maximum of the disturbance on the membrane to move toward their location. At another part of the modulating cycle these components are tending to cancel each other, while those at the opposite end are enjoying mutual reinforcement, and so the maximum of the disturbance finds itself in a new place. At intermediate times it is located between these two extremes. Now, if the location of this maximum is what determines the pitch of a tone, it is plain why the ear perceives a slow rate of frequency modulation as a continuous change of pitch, in spite of the fact that the stimulus really contains only a set of discrete tones. In other words, it is the beating among the components of the spectrum which gives us the *illusion* of a continuously changing frequency. (A schematic representation of this process is shown in Fig. 32, p. 91, in connection with the problem of the DL for frequency discrimination.)

What, then, is the nature of the effect under amplitude modulation? Here again we can say that if the ear were a better analyzer it would hear a group of steady tones whenever someone turns the intensity control of an oscillator up and down. Resolution is poor, however, and each component stim

ulates an extended area on the basilar membrane. These areas of disturbance alternately reinforce and interfere with one another, just as they do under frequency modulation, but with this one important difference—the maximum of the disturbance is never displaced from its position over the center of the spectrum. Phase relations are such that all the components work symmetrically to reinforce or cancel the central component without ‘skewing’ the pattern of disturbance. Consequently, the ear bears a tone whose loudness rises and falls, but whose pitch remains constant.

All these considerations pertain to modulations whose rates are not more than about 6 per second. We shall see later that additional complications may arise at faster rates, for then the components are spaced farther apart on the basilar membrane and the shift in the pattern of disturbance is too rapid to be perceived as a change in pitch.

AMPLITUDE MODULATION INTERRUPTED TONES

The last chapter showed how most of the experiments on auditory persistence are really experiments on the effects of amplitude modulation. Later we shall see how some of the experiments on frequency modulation can be regarded as experiments on persistence. Here, however, we shall investigate experiments on interrupted tones.

In their well known experiment, Weinberg and Allen made an effort to interrupt a tone issuing from a closed box by means of a rotating disk which had four symmetrically placed holes in it. The tone was heard when the holes of the disk coincided with a hole in the box. When the disk was rotated rapidly enough, the interruptions were not detectable. The authors therefore concluded that, when the interruptions are sufficiently frequent, fusion occurs—as it does in vision.

Wingfield, however, repeated this experiment with more adequate technique, but was unable to demonstrate fusion when the interruption of the tones was complete, regardless of the rate of interruption. By arranging his apparatus so that the cut

off was only partial, allowing some sound to reach the observer all the time, he could obtain fusion of the sort previously reported

Now, it is clear that these experimental conditions were such as to produce an amplitude modulation. If the cut-off had been instantaneous, the modulation would have been what we term 'square topped', and the resulting spectrum would have contained an infinite number of components distributed in groups of continuous bands. As it was, the cut-off, although not exactly sinusoidal, was sufficiently gradual so that the spectrum probably contained a finite number of components, spaced apart at a distance equal to the rate of the interruption. An increase in the frequency of interruption would then serve merely to move the components farther apart, and to increase the rate with which they beat with one another. Hence, at no rate of interruption, no matter how great, could we expect to free the resulting sensation from the effects of these side bands, unless the range of modulation were so small as to reduce these side bands to a negligible intensity.

When Wingfield made the cut-off only partially complete the effect was simply to reduce the range of the modulation which in turn reduced the magnitude of the side bands. Then with these side bands sufficiently small a point could be reached at which the central band alone was perceived. This is the point where fusion was supposed to have occurred but the present analysis shows us that it can be no question of the fusion of successively discrete stimulations because we are here dealing exclusively with steady tones. The large central component will always appear steady and unvarying to the listener whenever the alternate reinforcement and cancellation it receives from the side bands are less than the DL for intensity discrimination. It will be recalled in fact that Niesz used essentially this same method of interfering tones to measure DL's of intensity (Chapter 5 pp 136-141).

With rapid rates of modulation—rates equal to half the frequency of the tone itself—it has been shown experimentally that fusion does not occur. Kucharski was able to eliminate

every other cycle from a 200- and a 1000-cycle wave, a process equivalent to a square topped amplitude modulation at the rate of 100 and 500 cycles, respectively. Both these modulated tones, far from giving a clear impression of fusion, gave sensations differing markedly from those of pure tones. The interruptions in the 200-cycle tone were clearly perceptible as apparent breaks, but with the 1000-cycle tone the impression was more one of roughness. In both cases the central component was still detectable, i.e., trained observers could detect a pitch corresponding to 200 and to 1000 cycles.

DEMODULATION

We have seen (in Chapter 7) that, when two tones are present simultaneously, a difference tone may be heard. Consequently, when the amplitude of a wave is modulated in such a way as to produce three component frequencies, we should expect the ear to hear a tone equal, in frequency, to the difference between the components, provided the difference is large enough. That the ear does behave in this manner can be shown by modulating a 1000-cycle tone at the rate of 60 per second (Stowell and Deming). In addition to the three components, generated by the process of modulation, one hears a 60-cycle tone, generated by the process of *demodulation*. Demodulation occurs whenever a modulated wave is passed through a distorting system which partially rectifies the wave. The nonlinearity and asymmetry of the auditory mechanism produce just this sort of rectifying effect, so that we tend to hear the modulating frequency whenever this frequency is not too low.

Stowell and Deming were able to show that the loudness of the modulating tone (60 cycles) is, as we should expect, a definite function of the range of the amplitude modulation. No audible demodulation occurred, in their experiments, when the range of modulation was less than 4 per cent of the amplitude of the 1000-cycle tone. They also found that the frequency of the modulated tone is an important factor in determining how loud the 60-cycle tone will sound. In other words, more de

modulation occurs at some frequencies than at others. In their experiment, demodulation was most prominent for tones near 1000 cycles, and was absent at very low and at very high frequencies.

FREQUENCY MODULATION THE VIBRATO

The vibrato has long been utilized as a melodic embellishment that can be added to any note. The singer and the violinist, in particular, find that mastery of the vibrato is an important refinement of their art. With violin music it is clear what the physical nature of the vibrato is, for the violinist produces this musical effect by a rapid alteration of the length of a vibrating string by the movement of his finger, thus producing a frequency modulation. What the singer creates in the way of modulation becomes clear only by the analysis of his actual vocal production. The extensive studies carried out at the University of Iowa (Seashore) have yielded analyses of the vibrato as it is developed in the renditions of recognized artists. These investigations confirm the impression that the vibrato is essentially a frequency modulation, regardless of whether it is produced by instrument or by voice, but they reveal the additional fact that it is not uncommon to find present a small degree of amplitude modulation as well.

The average rate of the vibrato is about 7 fluctuations per second, but the rate among the better musicians is higher than among the less skilled. The range of the vibrato among violinists is about one-eighth of a tone (where range is defined as half the total extent), and among singers it is about one-fourth of a tone. Singers, however, show less uniformity than violinists.

These are the essential facts pertaining to the vibrato as it occurs in musical practice. The concern of the psychophysicist is not so much a matter of what the artist does as what the effect of his performance is upon the ear. How does the ear respond to modulations of rate and range used by musicians, and what are the critical values of these two variables in the production of certain subjective effects?

As an example of the kind of problem arising in frequency modulation, let us consider a specific instance. We can arrange a rotary condenser in the plate circuit of an audio-oscillator, so that, as the condenser revolves, the capacitance changes periodically and produces a periodic change in the frequency of oscillation of the oscillator. Such a device gives us a practical method for imposing a frequency modulation upon a tone. Now, suppose we adjust the condenser to give a range of modulation equal to 10 cycles when the oscillator is generating a 500 cycle wave. The frequency would then vary continuously and sinusoidally (given the proper form of condenser plates) between 490 and 510 cycles. The condenser, we shall assume, is being driven by a motor, and makes 1 revolution per second. What would the resulting tone sound like? The listener would hear a pitch which appeared to rise and fall continuously, over an extent equal to about a semitone. The actual stimulus, we know, consists here of a rather complex spectrum containing many individual tones spaced 1 cycle apart, but after these components reach the basilar membrane they reinforce and cancel one another in just the right sequence to cause the maximum of the disturbance on the membrane to move back and forth.

Now, let us increase the speed of the rotary condenser. As the rate of modulation rises, what we observe is that the pitch of the tone moves up and down more and more rapidly, but, with continued increase, a point is finally reached where the change in pitch vanishes, leaving instead an apparent intermittent change in intensity. The critical rate at which the ear begins to hear a single pitch, composed of intermittent pulsations, is about 6 alternations per second in the example we are discussing. Further increase in the rate to as high as 12 per second leads to an experience of a group of tones rather than a single pitch. The side bands in this instance would be found 12 cycles apart.

Another approach to the problem is to set the rate of modulation at a fixed value and change the range by altering the distance between the plates of the condenser. This procedure

would not change the position of the side hands in the spectrum of the tone, but it would alter their relative amplitudes. As the range increases, the amplitude of the outer side hands grows larger, making the spectrum effectively wider. How does the width of the spectrum affect our sensation? Within certain limits, it appears to determine the *richness* of a tone. Thus, as the range is increased steadily from zero, a point is eventually reached at which the tone appears, to the musical ear, maximally rich. Then, after further increase, the richness gives way to an experience of increased complexity.

Both these approaches were used by Ramsdell in order systematically to determine the critical values of rate and range for maximal richness and for singleness of pitch. He employed trained musicians as observers, because the judgment is essentially a musical one, and he gave them instructions, at one time, to increase the rate of modulation until they achieved a tone of apparently unitary pitch, such as would be satisfactory in a singing voice. At another time they were asked to vary the range until they obtained maximal richness. The results for four different frequencies are shown in Fig. 97. The circles show the values obtained when the rate was increased from a low value up to the rate which just gave singleness of pitch. The upper part of the curve has been dotted to represent the rates at which a gliding pitch is no longer detected and all that remains is a complex mass of tones. The almost vertical lines represent the results of adjusting the range of modulation to give maximal richness. At the intersections of the two functions we have what might be called the *richest singlest* note obtainable under frequency modulation.

How, then, do these critical values of rate and range compare with those of actual vibratos produced by good musicians? On the plot for the 500-cycle tone in Fig. 97 is indicated the rate and range of a group of 20 voices studied by Metfessel. About half his cases fell within the limits of this circle (provided we may assume that all the notes he studied were sung at 500 cycles). Here we see that most vocal vibratos are just fast enough to produce a note which appears unitary in pitch, and

that they cover very nearly the optimal range for maximal richness. The violinists studied by Hollinshead produced vibratos, most of which fell within the oval figure. The rates are very nearly the same as those of the singers, but the range is definitely

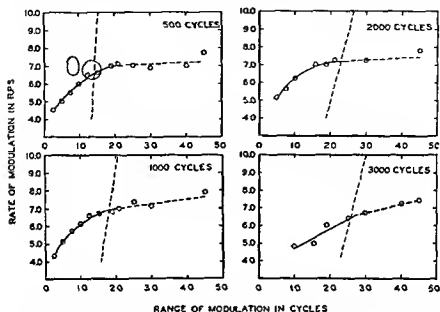


FIG 97 The critical rates and ranges of frequency modulation producing singleness of pitch (circles) and maximal richness (vertical dotted lines) (After Ramsdell) In the plot for 500 cycles, the large circle represents the rate and range of vibrato in the voices of accomplished singers, and the oval shows the rate and range of vibrato produced by expert violinists

smaller. The rates could be lower without the listener's being able to hear the tone as having a gliding pitch, but the range would have to be almost doubled to obtain maximal richness

Explanation of all the effects of frequency-modulation cannot be made at present. Probably the most interesting problem demanding clarification is why, as the rate of modulation is increased, we go from a situation where the pitch is obviously gliding up and down to one in which the only thing apparent is a series of intermittent impulses resembling rapid beats. At slow rates, the steady components beat with each other and cause the maximum of the disturbance on the basilar membrane to glide back and forth, in the manner already indicated. That

much is clear. But then, as the rate is increased, although the maximum continues to move back and forth, the movement no longer appears as a change of pitch. After the rate reaches 7 per second, no matter how extensive the excursion of the maximum on the membrane (no matter how wide the range of modulation), its gliding character is lost. Hence, 7 per second appears as the limiting value for the preception of this phenomenon. In terms of the two limiting positions of the maximum of the disturbance, it would appear that if they succeed each other less often than 7 times per second they can be perceived as occurring successively in time. At faster rates they appear in perception as occurring simultaneously. (This rule holds for wide ranges of modulation, where the end positions of the disturbance are far apart.) In other words, if the disturbance alternates between two positions within 0.14 sec, it does not appear successive. The figure of 0.14 sec reminds us that Békésy reported that the persistence of an auditory sensation lasts about this length of time (p. 222). Hence, it is not unreasonable to suppose that the two stimulations, due to the disturbance when it is at the two ends of its excursion, are perceived as simultaneous when they have not had time to die out to some definite value (not necessarily zero) before stimulation recurs. Just what this value is has not, as yet, been determined.

This unproved, but suggestive, relation between the critical rate of modulation and auditory persistence would mean that, whereas most experiments on persistence have turned out to be experiments on amplitude modulation, certain experiments on frequency modulation yield information relative to the decay of auditory sensations.

Now, it is clear from Fig. 97 that the experience of a gliding pitch may vanish at rates below 7 per second, but that then the range is definitely smaller and the disturbance on the basilar membrane does not move so far. This fact is apparent if we plot the spectra of the modulations giving singleness of pitch for the 500-cycle tone. These diagrams, presented in Fig. 98, reveal how much narrower is the spectrum which gives unitary pitch at a rate of 4.5 cycles than that which does not appear

unitary until the rate of 7 cycles is reached. Another important difference between these spectra is the predominance of the central component at the lower rate. When this component is large, and when the spectrum is narrow, the maximum of the disturbance moves back and forth, but, when the maximum is at one end of its excursion, the part of the membrane located at the position corresponding to the other end of the excursion is still being stimulated almost to the maximal extent. In other words, when the range of modulation is narrow, the difference between maximal and minimal stimulation at any one place



FIG. 98. The spectra for a 500-cycle tone whose frequency is modulated at the rates and ranges indicated. These rates and ranges are the critical ones which produce singleness of pitch.

on the basilar membrane is not so large as when the range is wide, and the maximum is, therefore, not so prominent. Under these conditions a relatively slow rate will obscure the movements of the maximum, and the pitch will not appear to glide up and down.

THE PITCH OF FREQUENCY MODULATED TONES

Tiffin and Seashore summarized the earlier work on the vibrato with a statement to the effect that the vibrato, due to frequency modulation, is heard as one salient pitch corresponding very nearly to the mean frequency of the modulation, and that, when the range of the vibrato is wide, the pitch is less accurately determined. A consideration of the spectra of satisfactory musical vibratos would lead us to believe that the pitch

of all vibratos is less certain than that of a single pure tone. Furthermore, it is quite possible that a very useful aspect of the vibrato, from the musician's point of view, is precisely this uncertainty of pitch, for it covers up slight errors in tuning. If a singer with a good vibrato sings slightly off key, the audience will be unaware of it.

Since a modulated tone has a spectrum composed of several steady tones, we are led to ask whether any of the components in a vibrato can be heard separately. In order to investigate this problem, three tones were modulated at the rate of 8 per second (Youtz and Stevens). The ranges were so chosen that the

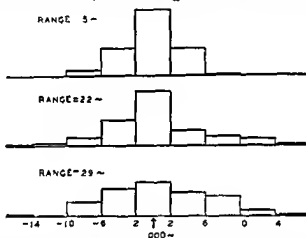


FIG. 99 The distributions of judgments of observers who set a pure tone to equal a tone (1000 cycles) modulated in frequency at the rate of 8 per second. The ranges of modulation are indicated on each plot. (After Youtz and Stevens.)

central component of the resulting spectrum was twice as large, equal, and half as large as the two adjacent side bands. These ranges were 15, 22, and 29 cycles, respectively, and the central component had a frequency of 1000 cycles in each case. The observers adjusted the frequency of a steady tone until it sounded equal in pitch to the modulated tone. Figure 99 shows the distributions of the settings. The wider scatter of the judgments at the wider ranges demonstrates that pitch becomes less certain as the extent of the vibrato is increased.

Closer analysis of the results from individual observers in this experiment revealed evidence that, when the range of modulation was 29 cycles, the separate components of the spectrum stood out sufficiently to cause occasional close groupings of the settings around one of the two large side bands. Even more direct, however, is the evidence from the verbal reports of the observers. When they raised the frequency of the test tone up to the value of pitch which they thought they detected in the modulated tone, they found that the pitch of the modulated tone had apparently moved still higher. Then, when they moved the pitch of the test tone on up to the new pitch in the modulated tone, they found that this pitch had unaccountably shifted back to its original value. In other words, whenever they had set the test tone to the pitch of one of the large components of the vibrato, the pitch of the other component stood out so clearly as to make the setting seem erroneous. The observers never could make a single pure tone match, at one time, all the pitches in the modulated tone. From this fact, we may conclude that, when the range of a vibrato is sufficiently wide, the individual components of the tone stand out well enough to be identified separately.

BEATS

Whenever two tones, of nearly the same frequency, are sounded together they produce beats at a rate equal to the difference between their frequencies. Beats occur because the continuous change in the relative phase of the two tones leads to alternate periods of reinforcement and cancellation. However, beats do not occur unless the two tones affect the same system. If the ear were a really perfect analyzer of sound, if Ohm's law held exactly, we should never perceive beats. It is only because the two tones force into vibration overlapping regions of the basilar membrane that an alternate waxing and waning of sound is heard. This lack of sharp tuning in the ear also underlies, as we have already noted, the effects produced by modulated tones. In fact, we can classify beats as a kind of hybrid modulation in which the spectrum contains only two

components. Beats are a combined amplitude and frequency (or phase) modulation.

When two tones are sounded simultaneously and the difference between their frequencies is gradually increased from zero, three successive stages of the phenomenon are distinguished: (1) the loudness appears to surge up and down continuously, (2) the beats are heard as a series of intermittent impulses, and (3) there is roughness without intermittence. The boundaries between these stages are not sharp, but the character of the sensation within each stage is quite distinct (Wever, 1).

The first stage begins at an indefinitely low rate. The slowest rate of beating that can be detected is probably determined only by the patience of the listener. Wever reports listening to beats as slow as one in two minutes. At that rate he heard the tone rise and fall very slowly in loudness, and these rises and falls were separated by periods of complete silence. When the rate is increased to the vicinity of 2 or 3 beats per second we find that the waxing and waning of loudness is very prominent. This is the rate at which beats are most easily detected (cf Fig 53, p 137).

At the rate of about 6 or 7 beats per second, where the second stage begins, the smooth rise and fall in loudness vanishes and each beat appears as a single impulse. We have already seen that, at this same rate of modulation, the pitch of a vibrato ceases to rise and fall as it does at lower rates. Beyond this critical rate, we are left, in both instances, with a tone having an intermittent, throbbing character. So similar are the sensations in the two instances that the ear has great difficulty in distinguishing certain vibratos from rapid beats.

Then, as the rate of beating increases further, the intermittent aspect gives way to roughness, and the third stage begins. The rate where this transition occurs is indeterminate. For one thing, it depends upon the frequency of the beating tones. Wever places the rate at about 166 for tones in the neighborhood of 1000 cycles.

The upper limit for the perception of beats, in the form of roughness, also cannot be set with precision, but the evidence

clearly indicates that this limit is higher when the beating tones are of high frequency. Intensity is also a factor in determining this limit, although systematic studies of its effect at different frequencies appear not to have been undertaken.

Regarding the apparent pitch of a beating complex, Wever was able to conclude, from a consideration of most of the evidence gathered by previous writers, that (1) When the difference between the frequencies of the two primary tones is low, the perceived pitch appears to lie between the primaries. The tone whose pitch is thus perceived is called the *intertone*. (2) With a greater difference in frequency, the two primaries step in beside the intertone. This change probably occurs at about 8 beats per second. (3) With still greater difference in frequency, the intertone disappears and the primaries alone remain. (4) When the primaries are sufficiently separated in frequency so as not to stimulate overlapping regions on the basilar membrane, these two tones are perceived as clearly distinct and without any roughness due to beating.

From our general notions regarding the spread of disturbance in the cochlea, we should anticipate that the amount of overlapping would be less for small than for large intensities. In fact, tones which normally give good beats may cease to do so when they are both made very weak. Casual observation has demonstrated this possibility. On the other hand, when two tones are very near in frequency and both are slightly below the auditory threshold in intensity, they may become audible during the period when their phases are such as to reinforce one another. Under these conditions, two inaudible tones produce audible beats.

The general rule regarding intensity is that beats are maximally prominent when the intensities of the primaries are equal. It is only then that two tones activating the same system can completely cancel each other during the period of phase-opposition. When one tone is less intense than the other, the cancellation is only partial, and, when the net change in amplitude of the stronger tone due to interference from the weaker tone does not attain a certain minimal value, no beats

are heard. The determination of this minimal value was precisely the goal of Reisz's experiment, which we discussed in connection with DL's for intensity (pp. 136-141).

It must be noted that, just as two primary tones may produce beats, so may any of the harmonics of these tones, regardless of how the harmonics are generated. Particularly interesting is the possibility of hearing beats between various harmonics of two tones when the harmonics are generated in the ear (see Chapter 7). The presence or absence of roughness created by the beating of aural harmonics may determine, according to the well known theory of Helmholtz, whether two objectively pure tones appear consonant or dissonant, when sounded together.

Finally, one may consider the relation between beats and difference tones. Since they both occur at the same frequency, people have sometimes tended to confuse them, and to speak of the difference tone as though it were merely the tone perceived as a result of rapid beats. Actually, however, beats and difference tones have essentially nothing to do with one another. They are produced by two entirely different principles. If the ear were a more sharply tuned analyzer, we should hear no beats, but we should still hear difference tones. On the other hand, if the ear were a linear system, producing no distortion, we should hear no difference tones but we should still hear beats. As it is, we hear both beats and difference tones simultaneously. Let us note the effect in the cochlea when two tones, 2000 and 2200 cycles, are sounded simultaneously. The two tones stimulate regions on the basilar membrane which overlap to some extent, and in this region of overlap interference occurs and produces beats. However, during the transmission of the two tones to the inner ear, distortion has occurred, producing a new frequency—the 200-cycle difference tone. This component frequency activates a region of the membrane near the helicotrema which vibrates quite independently of the beating that takes place elsewhere.

THE MEASUREMENT OF ROUGHNESS

Although in discussing the three stages which can be detected in the phenomenon of beats, Wever has distinguished roughness (the third stage) and intermittence (the second stage), this distinction is very much dependent upon the criteria of judgment brought to bear by the listener. It is quite plain that the stage of intermittence could equally well be characterized as "rough." Indeed, whenever a modulation occurs at a rate faster than about 20 per second, it engenders a sensation of roughness, and this roughness persists, although undergoing several qualitative transformations, until the rate reaches a high value.

Now, if we could select a suitable standard of roughness, it should be possible to determine the relative roughness of various

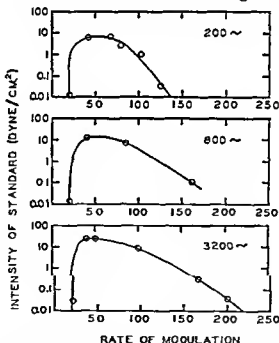


FIG 100 Showing how the roughness of tones (measured by the ordinate) changes with the rate of modulation (After Békésy 21)

sensations. Békésy (21) adopted as a standard the tones 3000 and 3050 cycles sounded simultaneously at equal intensities. The roughness of the resulting beats he could then control by

increasing or decreasing the total intensity of the beating complex, and the roughness of any other sound he could rate in units of this intensity, which he measured in terms of the maximal sound pressure of the beating tones. The ability of observers to give verifiable results justifies Békésy's choice of this standard.

In order to show the relation between roughness in an amplitude modulation and the rate of the modulation, Békésy equated his standard to three modulated tones, each having an intensity of 10 dynes per square centimeter. The results are shown in Fig. 100. The roughness rises to a maximum in each instance and then falls off with increasing rates of modulation. The low tone (200 cycles) loses its roughness more rapidly than either of the higher tones. This finding is consistent with the fact that the maximal rate for the perception of beats is higher at the higher frequencies.

Békésy's technique for the measurement of roughness also enables us to determine the effect on a beating complex of a change in the relative intensities of the two beating tones.

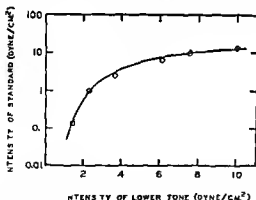


FIG. 101. Showing how the roughness of the beating of two tones 750 and 800 cycles changes with the intensity of the lower (750-cycle) tone. The 800-cycle tone had an intensity of 10 dynes per square centimeter. (After Békésy 21.)

Thus, when 750 and 800 cycles are sounded together at an intensity of 10 dynes per square centimeter, they exhibit a degree of roughness measured by the intensity of the standard combina-

tion (3000 and 3050 cycles), as pictured in Fig. 101. Then, as the intensity of one of the tones (750 cycles) is reduced to the various values shown on the abscissa, the roughness declines in such a way that the intensity of the standard must be reduced in order to hold the two roughnesses equal. At the limit, we might expect that, with sufficient reduction in the intensity of the 750-cycle tone, all roughness would disappear, and then, in order to be equally rough, the standard would need to be extinguished.

CHAPTER 10

THE MECHANICS OF THE EAR

WE HAVE studied, in the previous chapters, the nature of our sensations when we listen to auditory stimuli. We have examined the relation between our discriminatory responses and the dimensions of the stimulating sounds. These studies have been designed principally to answer the question, "*What* do we hear when we listen?" We shall now turn our attention more particularly to the mechanical and physiological processes involved in our auditory responses. We shall endeavor to see how the ear responds to sound waves and converts them into neural events which underlie the discriminatory reactions which we call *hearing*. In other words, we shall try to answer the question, "*How* do we hear when we listen?"

Sound waves are a type of atmospheric disturbance whose detection requires a specialized kind of mechanical system. The ear is precisely such a system. It is a very delicate and highly complicated mechanical device—certainly the most remarkable *mechanical* system in the human body. Its astounding sensitivity to minute disturbances, its ability to acquaint the brain with displacements of the eardrum which are smaller than the diameters of molecules (Chapter 2), and its power of resolving complex wave forms into their Fourier components make the ear a masterpiece of mechanical engineering. In order properly to understand the action of the auditory mechanism under the impact of sound waves, we must investigate it from the point of view of (1) its mechanical properties and (2) its function as a transducer capable of converting mechanical energy into nerve impulses. The nature of the latter function is disclosed chiefly, as we shall see later, by the electrical effects which accompany it. The mechanical properties of the ear we must understand, for the most part, by appealing to known mechanical principles, on the assumption that they hold

true in a system like the ear. This procedure necessitates careful anatomical measurement of the parts of the ear, especially of the middle and inner ear. In this chapter we shall review the essential anatomy of the ear and consider how it behaves as a mechanical system.

THE ANATOMY OF THE MIDDLE EAR

The *external auditory canal* of the human ear is about 2.5 cm long and 0.7 cm in diameter. It is closed at its inner end by the eardrum, or *tympanic membrane*, a cone shaped structure with its apex directed inward, which is placed somewhat obliquely across the end of the canal. Internal to this membrane lies the irregular shaped cavity of the middle ear, between 1 and 2 cc in volume, containing the three *ossicles* (*malleus*, *incus*, and *stapes*) and their supporting ligaments. In the medial wall of the middle ear cavity are two openings in the temporal bone, giving access to the inner ear. These, from their shapes, are known as the *oval window* and the *round window*. The round window is covered by a membrane, and the oval window is filled by the footplate of the stapes, which is held in place by elastic ligaments. Another opening into the middle ear cavity is the *Eustachian tube*, which connects with the nasopharynx. Ordinarily the Eustachian tube is closed at its lower end, but it regularly opens during the act of swallowing and thereby allows equalization of any difference in pressure on the two sides of the tympanic membrane. Figure 102 is a schematic diagram of the middle ear and also the vestibule, semicircular canals, and cochlea. The cochlea is here represented as straight, although actually it is coiled in the form of a snail shell of two and one half turns.

Figure 103A is a photograph of the three human ossicles. They are normally oriented one to another approximately as shown in the photograph, but the articular surfaces have there been separated. As Fig. 102 indicates, the handle of the malleus is firmly attached to the tympanic membrane, and its lower tip lies practically at the center of the membrane. Viewed through the external canal, the tympanic membrane appears

as a circle. Under proper illumination, the handle of the malleus can be seen through the membrane as a vertical radius. Malleus and incus articulate closely with one another by means of the large irregular surfaces illustrated in the figure. The joint is bound tightly by ligaments, and both ossicles are attached to the walls of the middle ear by elastic ligaments, so that they are free to vibrate in response to movement of the

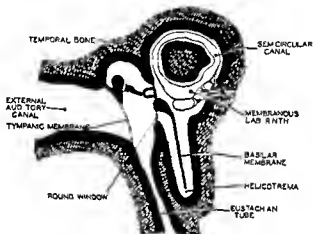


FIG 102 Schematic diagram of the internal ear. The cochlea is represented as straight instead of coiled. (After Bekésy 19)

handle of the malleus. The long process of the incus articulates with the head of the stapes. The footplate of the stapes is snugly sealed in the oval window by another elastic ligament. (For the dimensions of the ossicles see Stuhlman or Piersol.)

Two muscles attach to the ossicles. The smaller of these the *stapedius*, is attached to the head of the stapes close to its articulation with the incus. Its contraction draws the head of the stapes outward and downward in a direction opposite to the inward and upward movement of the long process of the incus caused by increase of pressure on the outside of the tympanic membrane. The other muscle, the *tensor tympani*, attaches to the handle of the malleus and draws it inward, thereby placing the tympanic membrane under tension. The effect of its action on the stapes is to force the footplate upward and

inward into the oval window, and its action is thus antagonistic to the action of the stapedius. When both muscles contract simultaneously, as they usually do, the effect is to bring the ossicles into closer approximation, to draw the tympanic membrane inward and increase its tension, and, since the tensor tympani is apparently more powerful than the stapedius, to force the footplate of the stapes inward.



FIG 103 *Left* Photograph of the malleus, incus, and stapes. The ossicles have been separated, but otherwise are in approximately their normal positions relative to one another.

- 1 — articular surfaces of malleus and incus
- 2 — incus
- 3 — footplate of stapes
- 4 — handle of malleus

Right Photograph of the medial wall of the middle ear, showing stapes, oval window, and round window. The stapes has been lifted out of the oval window and the tendon of the stapedius muscle has been cut.

- 1 — head of stapes
- 2 — footplate of stapes
- 3 — round window
- 4 — oval window

(Békésy, 19)

Neither of the intra-aural muscles is readily visible on examination of the middle ear, even at surgical operation, since they lie in bony canals and only their tendons project into the middle-ear cavity. Békésy suggests that this arrangement is most fortunate, in that the bony casing prevents the muscles from vibrating laterally when the ossicles transmit sound-waves. Such vibration of the muscles would distort the transmitted sounds.

ROUTES FOR THE TRANSMISSION OF SOUND
TO THE INNER EAR

Sound waves entering the external canal may reach the inner ear by three main routes. The most important is by means of the ossicular chain across the middle ear from the tympanic membrane to the oval window. The second of these routes also involves the tympanic membrane, but transmission across the middle ear is by means of air waves instead of by movement of the ossicles. These air waves fall upon the round window and cause vibration of the round window membrane exactly as the air waves in the external canal initiate vibrations of the tympanic membrane. The third avenue of approach does not involve the tympanic membrane. Sound-energy is taken up by the walls of the canal and transmitted through the bones of the skull around the middle ear to the inner ear. In this case of so-called *bone-conduction*, the sound need never enter the external ear, but may be picked up directly by the skull. If the skull touches a hard vibrating object, this form of conduction becomes important and it may be employed to practical advantage in the event of damage to the mechanism of the middle ear (see Chapter 11).

It has long been known from clinical experience that restriction of the movement of the ossicles by adhesions resulting from old inflammatory processes or by bony union of the stapes with the margins of the oval window seriously reduces the efficiency of the middle ear as a transmitting mechanism. Likewise, a disruption of the ossicular chain may greatly impair the efficiency of the middle ear, but it has not been possible to study experimentally in man the effect of simple interruption of the continuity of the ossicular chain. In animal experiments, however, where the electrical activity of the cochlea (see Chapter 13) may be used as an indicator of sound transmission, we may compare the efficiency of the middle ear before and after disarticulating the incudostapedial joint and removing a small piece of the incus. The elevation of threshold resulting from this operation is about 60 db on the average (Wever and Bray, 7).

It is also known, as a matter of practical experience, that a rather extensive hole in the eardrum causes only very slight loss of hearing. Lorente de Nó and Harris used the reflex contraction of the stapedius muscle as indicator of sound transmission in the ears of animals, and showed that it is even possible to cut entirely around the tympanic membrane and cause a hearing loss of not more than 20 or 30 db. More surprising, however, is the observation that some individuals who have lost, not only the tympanic membrane, but also malleus and incus may nevertheless retain hearing that is within 20 or 30 db of normal. Such cases are exceptional, however. Usually when drum, malleus, and incus are missing, the sensitivity of the ear is reduced by 40 to 65 db. Figure 104 shows the loss of sensitivity

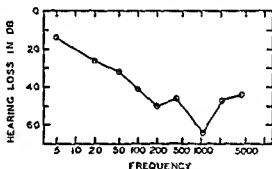


FIG 104 Average hearing loss of five ears without tympanic membrane, malleus or incus, referred to the average sensitivity of the normal ears of the same individuals. (After Bekesy, 25)

of five such ears compared to the average sensitivity of the normal ears of the same individuals.

When the drum and one of the major ossicles are missing, hearing occurs by air-conduction direct to the round window (Békésy, 25). Then the waves of sound-pressure reach the sensory mechanism in opposite phase to the waves carried in by a normal ossicular chain. This difference in phase is understandable when we recall that waves brought by the ossicles are delivered to the oval window, whereas air borne waves have easiest access to the round window. Round and oval windows communicate with the endolymphatic channels on opposite sides of the basilar membrane (cf Figs 102 and 105), and a wave of

positive pressure causes, in the one case, upward, in the other case, downward, movement of the basilar membrane. The proof that such a difference of phase actually occurs consists in allowing two observers, one with normal ears, the other with one ear normal and the other ear lacking drum and ossicles, to listen with the right ear to one source of sound and with the left ear to another. Tones of slightly different frequency are then delivered to the two ears. The listeners experience a source of sound that seems to shift its position as the phase of the sound waves reaching the two ears varies (cf Chapter 6). The normal individual and the subject with one damaged ear localize the apparent source of sound on opposite sides of the median plane, showing that the phase of the sound waves has been reversed in the abnormal ear. When the abnormal ear is then provided with an artificial membrane and an ossicle consisting of a fine bristle attached to the artificial membrane and touching the promontory of the petrous bone, the hearing of that ear is somewhat improved (cf also Pohlman, 3), and the phase relations of the sounds heard by it are restored to normal.

THE SIGNIFICANCE OF THE ROUND WINDOW FOR HEARING

The experiments just described show that sound waves can enter the inner ear by way of the round window. Since they affect the mechanism of the inner ear in opposite phase to those transferred by the ossicles and oval window, they must tend to reduce the effectiveness of the latter. It would seem, therefore, that the round window is a hindrance to the most effective working of the normal auditory mechanism. Some support for this view is to be found in the experiments of Hughson and Crowe, who utilized the electrical activity of the cochlea and auditory nerve as a measure of hearing. When they placed pledgets of cotton on the round window, the electric potentials increased. A similar effect was produced by placing a periotic graft over the round window and testing the animals from two days to seven weeks later. It is probable that the improvement of response resulted not so much from 'immobilization

of the round window and prevention of loss of energy from within the inner ear, as Hughson and Crowe believed, as from protection of the round window from interfering air borne sound waves. If the walls of the cavity of the inner ear were rigid throughout, no movement of fluid in the canals of the cochlea would be possible, and the basilar membrane would not vibrate. The round window forms an elastic termination of the scala tympani, and thereby allows movement of the endolymph and vibration of the basilar membrane. If, therefore, the round window membrane is too rigidly fixed, a diminution in auditory acuity should result. If, however, it is not rigidly fixed, but partially protected from air borne sound waves, some improvement of hearing might occur.

THE MECHANICS OF THE OSSICLES

In animal experiments and in post mortem studies on human ears, tiny mirrors have been attached to the tympanic membrane or to various ossicles (Krainz, Dahmann, Békesy, 25). It is thus possible to record photographically the direction and amplitude of the movements not only in response to sound, but also in response to contraction of the intra aural muscles and to increased atmospheric pressure.

The malleus and incus are so closely bound together that, in response to moderate pressures, they vibrate as a single unit by rotating about an axis in the ligament supporting the malleus. In fact, as long as the amplitude of vibration of the ossicular chain is so small that the stapes readily can follow it, and as long as the ossicular joints offer greater resistance than the fixation of the stapes in the oval window, the whole chain vibrates as a closed mass. All the ossicles respond to high as well as to low tones with measurable vibrations. All the ossicles, as might be expected from their elastic suspension, may move in several planes, but one principal plane predominates. This plane corresponds to the in and-out movement of the handle of the malleus and the long arm of the incus. The effective lever arm of the incus is slightly longer than that of the malleus, so that the amplitude of motion delivered to the stapes is increased in

comparison with that of the handle of the malleus at the center of the tympanic membrane in the ratio of 4 to 48.

The stapes does not move directly in and out like a piston, but rocks like a bell-crank lever. Examination of the ligament which attaches it to the border of the oval window shows that the ligament is thick and tight at the lower posterior pole and is broad and thin at the upper anterior pole. The lower posterior pole acts as a fulcrum about which the stapes rotates (Fig. 105). The movement of the long process of the anvil is

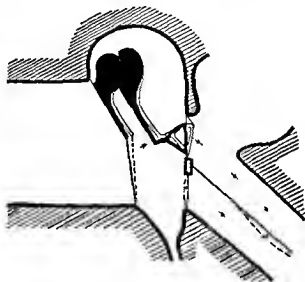


FIG 105 Schematic diagram of the tympanic membrane, the ossicles, and the basilar membrane. The solid figures of the ossicles and the solid lines for the tympanic, the basilar, and the round window membranes show the positions of these structures at rest. The open outlines of the ossicles and the broken lines for the membranes show their positions following inward displacement of the tympanic membrane by a sound wave. (See Fig. 102 for names of structures.)

so directed as to produce the bell-crank movement of the stapes most efficiently. When the intensity becomes very great the mode of vibration of the stapes alters, so that instead of pivoting at its posterior pole it rocks about the long axis of the footplate (Békésy, 25). This change of vibration reduces the resulting movements of the fluid in the inner ear and serves as a protective

mechanism The change is made possible by the relative flexibility of the incudostapedial joint, and the level of stimulation at which it occurs Békésy identifies with the threshold of pain and tactile sensations in the ear (see Fig 19, p 59)

It should be noted that Dahmann's view that incus and malleus vibrate as a closed system is opposed to the earlier concept of Helmholtz that there was sufficient movement in the joint between these two ossicles to allow of the effective delivery of positive pressure to the stapes, but not of negative pressure As a matter of fact, large alternating pressure applied to the tympanic membrane causes more movement of the malleus outward than inward The movement of the incus shows the same asymmetry but to a lesser degree The movements of the stapes are more nearly, but not entirely, symmetrical (see Fig 106)

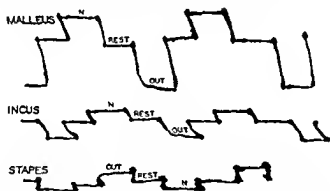


FIG. 106 Photographic record, obtained by mirrors attached to the ossicles showing the displacements of malleus incus and stapes produced by equal pressures inward and outward applied to the tympanic membrane. The displacements outward are greater than the corresponding displacements inward as shown by the vertical components of the records (After Dahmann)

Additional insight into the mechanics of the ossicular chain and the basis of its nonlinear performance has been obtained from experimentation upon a carefully constructed model of the ossicles (Stuhlman) The nonlinearity depends upon the flexible character of the joint between the malleus and incus The performance of the structure is more nearly linear the more rigidly this joint is locked If the articulation is loose, the ratio of movement of malleus to incus is 2 to 1 for inward motion

and 1 to 1 for outward motion of the tympanic membrane. The motion of the malleus pushes the incus backward, while the lenticular process at the end of the long crus of the incus passes through a complex three-dimensional displacement somewhat resembling the rolling of a pestle in an oval bowl. The displacement of the footplate on outward motion of the malleus is twice as great as it is for the same inward motion. The forces developed under these conditions are summarized in Fig 107.

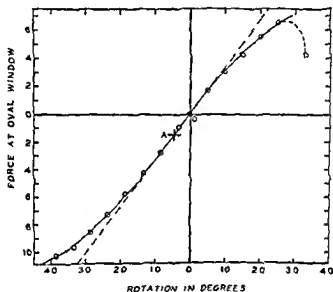


FIG 107 Graph of the force exerted on the stapes as a function of the degrees of rotation of the malleus. Note the nonlinearity and asymmetry of the curve as a whole. Point A, at the middle of the central linear portion of the curve, is the point about which the curve is most nearly symmetrical. It does not coincide with the position of rest (0).

Inward rotation of 30° dislocates the malleo-incudal joint. The resulting decrease in pressure on the stapes is indicated by the broken line at the upper end of the curve. The measurements were made on a scale model of the ossicles. (After Stukelman)

Extreme inward motion of the malleus dislocates the joint between malleus and incus, but dislocation does not occur on outward motion. This dislocation may well serve as a mechanical protective device against great inward pressures.

The loose coupling of the malleo-incudal joint is an impor-

tant source of asymmetry and nonlinearity in the mechanical performance of the auditory mechanism, but it should not be regarded as the sole factor. The various elastic structures, such as the drum, the ligaments of the ossicles, and the basilar membrane may all contribute to provide for the ear a characteristic like that shown by the curve of Fig 82 (p 195)

THE IMPORTANCE OF THE OSSICULAR MECHANISM

The complicated chain of ossicles found in mammals is not essential for hearing, but it probably does represent an increase of efficiency over the simpler mechanism in birds. The bird has, instead of three ossicles, only a single bone, the columella, which is analogous to the stapes. It is worth noting that the inner ear of the bird is also more primitive than that of the mammal. The rods of Corti and the tunnel (cf Fig 113) are missing, and simply a group of sensory cells and supporting cells lie along the basilar membrane (Retzius)

The effect of the tympanic membrane and ossicular chain in improving the efficiency of hearing is fourfold. First, they provide for preferential delivery of sound-energy to the oval window as opposed to the round window. Second, they serve to collect energy from a relatively large cross-section of air and deliver it to the much smaller area of the footplate of the stapes. This, as will appear below, is an important advantage in passing from air as a conducting medium to a fluid such as the endolymph. Third, they provide a slight mechanical reduction in amplitude of motion between the tympanic membrane and the part of the stapes which is directly in contact with the fluid of the cochlea. Finally, in conjunction with the intra aural muscles, they provide a protective mechanism for the inner ear against loud low tones without undue impairment of hearing for faint tones of high frequency (see p 267)

THE ACOUSTIC IMPEDANCE OF THE EAR

Any physical system capable of vibration presents a certain resistance, or, more broadly, an *impedance* to vibratory energy

delivered to it. This is analogous to the impedance which an electric circuit presents to the flow of current. The greatest efficiency in the transfer of energy from one system to another is attained when the impedances of the two systems are equal. Air and water differ widely in density and elasticity, and consequently in acoustic impedance whenever equal cross-sectional areas are juxtaposed. This principle is clearly recognized by engineers in the problem of producing and detecting sound waves in water by submarine signaling devices. In going from air to water a large cross section of air should be coupled to a small cross section of water, if the device is to be efficient.

The ossicles, as a lever system, connect the tympanic membrane, whose cross-sectional area is approximately 90 sq mm, with the footplate of the stapes, whose area is 3.2 sq mm. The full significance of this ratio of 90 to 3.2 is uncertain, because neither the tympanic membrane nor the stapes moves in and out as a rigid piston. The tympanic membrane is a flexible structure fixed at the edges, and the stapes rocks about one end of its footplate. This rocking of the stapes probably provides a slight reduction in the effective amplitude of the footplate as compared to the amplitude of the center of the tympanic membrane, but the motions of the ossicles are so complex and uncertain that the amount of the reduction has not been determined with exactitude. It is probably of the order of 2 to 1. This reduction, plus the difference in area between the tympanic membrane and the footplate of the stapes, aids in matching the impedance of the inner ear to that of air. Whether this match is exact or not we do not know, for we have not determined the exact impedance of the inner ear. The acoustic impedance of the ear as a whole has been measured, however, and the comparison of its value with that of air gives an indication of the efficiency of sound-detection by the ear, irrespective of how the matching is brought about. Troger devised a method for measurement of the acoustic impedance of the ear, which depends upon the production of standing waves in a tube system whose end is closed by the tympanic membrane. He deduced, from his measurements, that the membrane is to be regarded as a com-

plex impedance, having an elastic character, which is very great for low frequencies, but which reaches a minimum at 800 cycles (Fig 108) At this frequency, the efficiency of energy transfer must be high, since air and ear show the same numerical value for their impedances Measurements of the ears of various observers give good agreement up to about 600 cycles Above this value, each individual shows various points of resonance, and one subject may differ considerably from another, particularly near the points of resonance

A close relationship between the impedance of the ear and the threshold of sensitivity was found by Geffcken, who further showed that certain objections raised by Wien against the

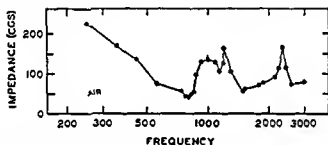


FIG. 108 Impedance of the human ear The units are in the centimeter gram second system On this scale the impedance of air is 40 as shown by the broken line. (After Troger)

resonance theory of hearing are met by recognition of the part played by variations in the impedance of the tympanic membrane with frequency It is also evident that the sharp minor maxima and minima found in individual threshold curves may well depend upon points of mechanical resonance, since the mechanical vibrating system of drum, ossicles, and inner ear is obviously very complex Each part may have a resonant point of its own which appears as a maximum or a minimum on any over all curve, whether for threshold or for impedance, which expresses the performance of the ear as a whole

At very low frequencies (below 100 cycles) the impedance of the ear is determined not entirely by the mechanical properties of drum, ossicles, and inner ear, but is modified significantly by the air in the cavity of the middle ear itself, which

acts as a cushion and tends to diminish slow excursions of large amplitude. Measurement of the acoustic impedance of the ear at a frequency of 5 cycles (Békésy, 24 and 25) shows that it is equivalent to a closed chamber approximately 20 cc in volume. This value agrees closely with the estimates of capacity based on purely anatomical studies (see p. 249). The normal air-cushion may act as a protective mechanism against sudden extreme changes in pressure or very loud sounds of low frequency. If, however, the membrane is perforated by a hole 1 mm square, the cushioning effect of the air in the middle ear is lost. When the middle ear is opened through the temporal bone without damaging the tympanic membrane, the impedance of the ear at 10 cycles corresponds to a volume greater than 80 cc. The mastoid air cells communicating with the middle ear cavity differ considerably from one individual to another and are often small enough to absorb sound and change the resonance of the middle ear.

THE NATURAL PERIOD OF THE EAR

Several direct measurements have been made of the natural period of vibration of the ear in response to sudden brief disturbances such as the sound of an electric spark. Figure 109 shows two records of the damped free oscillations of the malleus following stimulation by a sudden sound. A hole was drilled through the temporal bone of a human corpse and a tiny mirror attached to the handle of the malleus. The ear was then stimulated by the sound of an electric spark. The resulting patterns of vibration differed as shown in pictures *A* and *B* of Fig. 109, depending upon the form of the sound wave. Figure *B* illustrates with particular clarity the natural period of vibration of the structures of the middle ear and also the rapid damping of these vibrations. Frank and Broemser originally gave, as the natural frequency of the ear, the figure of 800 to 1500 cycles, which is confirmed by Békésy (25, 15). Kobrak's figures, 550 to 800 cycles, are a little lower, whereas Davis, Derbyshire, Lune, and Saul give 1200 to 1700 cycles for the cat. All agree that the over-all vibration of the ear is highly, but not critically, damped. Kobrak gives a damping factor equal to

about one half the value for critical damping. Under this damping the auditory mechanism executes a few rapidly damped oscillations at its natural period following sudden displacement from its position at rest and also following the sudden onset or cessation of strong stimulation at any frequency. This general 'off effect' is not to be confused with the Helmholtzian idea that specific portions of the basilar membrane continue to vibrate for a few cycles at the same frequency as the previous stimulating tone. The basilar membrane, although differentially sensitive in various regions to different frequencies, appears to be essentially critically damped, for the electrical activity of the cochlea shows, as an 'off effect,' only a nonspecific natural period which probably depends upon the vibrating structures of the middle ear (see Appendix II).

The damping factor, and also the natural period of the structures of the middle ear, are altered by contraction of the tensor tympani and the stapedius muscles (Dahmann). The transmission factor is reduced by 30 per cent and the elastic component of the impedance is increased during voluntary contraction of these muscles (Geffcken). The effect upon the sensitivity of the ear to various frequencies will be considered below, but all the changes seem to be those which we should expect on physical principles from an increase in the tension of an elastic vibrating structure.



FIG 109. Vibration of the ossicular chain in response to single clicks recorded by means of a mirror attached to the malleus (After Bekésy 25). Note the difference in time scales of *A* and *B*.

A—response to a sharp click.

B—response to a dull click, showing natural period and rate of decay of vibration with special clarity.

THE ACTIVITY OF THE INTRA AURAL MUSCLES

Contraction of the muscles of the middle ear has been studied directly in animals by attaching mirrors to the tympanic membrane or ossicles or by attaching a delicate myograph di-

rectly to the tendons. More recently the electrical activity of the cochlea has been employed in order to observe the effect of contraction upon the transmission of sounds. Lüscher has observed directly the movements of the stapedius in a human subject with a defective tympanic membrane. Occasionally it is possible to appreciate the contractions of one's own ear muscles by listening to the faint sounds which may be produced by the movements of the ossicles or by crepitation of wax on the external surface of the membrane. Ordinarily, these movements are silent, or very nearly so, but with practice it is often possible to apprehend them without much difficulty and also to learn to appreciate the direct sensation of stretching or movement associated with the contraction. A few individuals are able to contract their intra aural muscles voluntarily.

From the combined results of human and animal observations the muscles of the middle ear appear to contract reflexly in response to irritation of the external canal, of the pinna, or of a considerable area of skin surrounding the external ear. Light stroking or tickling may be enough to elicit this response in man, and in the rabbit, under light anesthesia, stimulation of the cutaneous auricular nerves gives excellent reflex responses. In the rabbit the reflex responses are essentially bilateral, whatever the source of stimulation (Lorente de No, 1). This is probably not generally true for man. One of the present writers (H. D.) finds that the responses of his own intra aural muscles to light cutaneous stimulation are essentially homolateral. Contraction of the muscles in question seems to occur regularly as part of the act of yawning. Whether this contraction is to be regarded as primarily included in the pattern of yawning or whether it is secondary to opening of the Eustachian tube is still uncertain.

A definite threshold for reflex response of the muscles to sound can be established. The threshold intensity in rabbits, under urethane anesthesia, is some 40 db above the threshold for human hearing (Lorente de No, 1). As a function of frequency, the threshold for reflex response parallels rather well

the human audibility curve, although it is relatively lower for very high tones, above 8000 cycles. The strength of the reflex contraction also varies directly with the intensity of the stimulating sound. Furthermore, the contraction tends to persist as long as the stimulating sound continues. It also appears that the stapedius reflex is the more sensitive to tones below 3000 cycles, whereas above this frequency the responses of stapedius and of tensor tympani have approximately the same threshold.

The latency of the contractions of these muscles to the sudden onset of a tone is 14 to 16 msec. Maximal tension is attained in 100 to 150 msec. These times are brief, and it is evident that the speed of action of the tensor tympani and the stapedius corresponds to the protective reflexes of the limb muscles and is not much slower than the blinking of the eyelids. In many ways, the action of these muscles should be compared with that of the eyelid and its musculature, rather than to the muscles of the iris of the eye which govern the size of the pupil, for the latter are slowly acting smooth muscles. However, like the muscles of the iris, the muscles of the middle ear also perform a protective and adjusting function in relation to their sense organ.

The acoustic reflex of the middle ear closely resembles the spinal reflexes of skeletal musculature generally, and, in common with them, is abolished by deep anesthesia (Hallpike, 2). It is probably for this reason that they have not been seen by more investigators of auditory function. It should be noted that any observation of the relation between the electrical phenomena of the cochlea and the intensity of stimulation (see Chapter 14) which is undertaken while this reflex is active may be modified by the effect of the reflex itself upon the transmission of sound across the middle ear (Hallpike and Rawdon Smith, 1). The effect of the reflex upon transmission may account for certain differences between the conclusions drawn from studies of intact animals and man and from studies of the ear in deeply anesthetized animals.

THE ANATOMY OF THE INNER EAR

The anatomy of the inner ear is described in the various standard textbooks of anatomy and, apart from details concerning the numbers of ganglion cells and the mode of innervation of the hair-cells, little has been added to our knowledge of this subject in recent years. It will be convenient, however, to review the arrangements of the essential structures and to define the various anatomical terms which will of necessity be employed in describing the behavior of the sense-organ in response to sound-waves impinging upon it.

In the temporal bone of the skull lies the internal ear with its sense-organ of hearing. It is called the *labyrinth*, from the

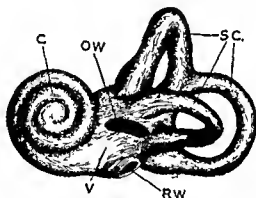


FIG. 111. Lateral view of the left osseous labyrinth. The figure represents a cast of the spaces and channels within the temporal bone. The membranous labyrinth lies within these spaces.

C — cochlea
V — vestibule

OW — oval window
RW — round window

S.C. — semicircular canals

complexity of its shape, and consists of two parts: the *osseous labyrinth*, a series of cavities within the petrous part of the temporal bone, and the *membranous labyrinth*, a series of communicating sacs and ducts contained within the bony cavities. The osseous labyrinth consists of three parts: the *vestibule*, the *semicircular canals*, and the *cochlea* (Fig. 111). They contain a clear fluid, the perilymph, in which the membranous labyrinth is situated.

The *vestibule* is the central part of the osseous labyrinth, and is situated just medial to the tympanic cavity of the middle ear. It measures about 5 mm from front to back, the same from top to bottom, and about 3 mm across. In its lateral wall is the *oval window* into which the footplate of the stapes is attached by its annular ligament. The three *semicircular canals*, superior, posterior, and lateral, open into the vestibule. They need not be considered in detail, as they are not concerned with the function of hearing. They do, nevertheless, form part of the total chamber to which changes of pressure, generated by movement of the footplate of the stapes, are delivered.

The bony *cochlea*, which is the part of the inner ear concerned with the reception of sound, lies horizontally in front of the vestibule. In shape it resembles a snail shell. It measures some 5 mm from base to apex, and its breadth across the base is about 9 mm. It consists of a conical central axis, the *modiolus*, and a canal, the inner wall of which is formed by the central axis, wound spirally around it for $2\frac{3}{4}$ turns. A delicate shelf of bone, the *osseous spiral lamina*, projects from the modiolus and partially subdivides the canal into two parts throughout its length. A tough membrane, the *basilar membrane*, stretches from the free border of the lamina to the outer wall of the bony cochlea, and completes the separation of the canal into two passages, except for a small communicating opening between them, the *helicotrema* at the apex of the modiolus. The cochlear division of the *eighth cranial* (auditory) *nerve* enters the modiolus at its base as shown in Fig. 112. The nerve cells are grouped as a long spiral ganglion (*Corti's ganglion*) opposite the osseous spiral lamina. The terminal filaments of the nerve emerge through small openings in the bony structure.

The canal of the cochlea has three openings—one the *round window*, or *fenestra rotunda* which looks into the cavity of the middle ear but is closed by the *round window membrane*. Another elliptical opening leads into the vestibule. The third, a much smaller opening, is the end of the *cochlear aqueduct*, a tiny canal leading through the temporal bone to the subarachnoid cavity at the base of the brain.

The *membranous labyrinth* lies within the bony cavities and has their same general form. It is considerably smaller and partly separated from the bony walls of the labyrinth by the

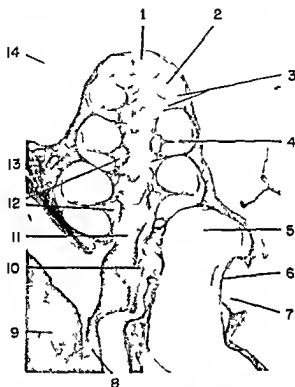


FIG 112 Section through the central axis of the cochlea of a guinea pig showing the auditory nerve passing up the center of the modiolus to the successive turns of the cochlea (Lurie unpublished.)

- | | |
|---|---|
| 1—helicotrema | 7—membrane of round window |
| 2—scala vestibuli | 8—beginning of cochlear nucleus |
| 3—scala media, above scala tympani, below | 9—medulla oblongata |
| 4—basilar membrane and organ of Corti | 10—internal auditory artery |
| 5—vestibular end of scala vestibuli | 11—auditory nerve to the internal auditory meatus |
| 6—oblique section through spiral lamina, organ of Corti and | 12—spiral ganglion of Corti |
| basilar membrane | 13—temporal bone |
| | 14—cavity of the middle ear |

perilymph The membranous labyrinth also contains fluid—the *endolymph*. Within the vestibule, the membranous labyrinth

does not form a single chamber, but consists of two sacs, the *utricle* and the *saccul*e, containing sensory epithelium and supplied by nerve fibers from the vestibular portion of the eighth cranial nerve. Neither utricle nor saccul is concerned with the function of hearing, although the suggestion has repeatedly been made that the saccul may play a part in the detection of vibrations or the hearing of low tones.

The sensory cells concerned with hearing are contained in the *ductus cochlearis*, a portion of the membranous labyrinth which is arranged as a spiral tube in the bony canal of the cochlea and lies along its outer wall on the basilar membrane. The basilar membrane forms the floor of the ductus cochlearis, and a second, much more delicate membrane (*Reissner's membrane*) extends diagonally from the osseous spiral lamina to the outer wall of the cochlea some distance above the outer edge of the basilar membrane. The ductus cochlearis, which is also termed the *scala media*, ends as a blind sac at the helicotrema. The portion of the canal of the cochlea above the scala media is the *scala vestibuli*, and the portion below the basilar membrane, the *scala tympani* (see Fig. 113).

The basilar membrane is a stout tendinous layer of closely adjacent fibers. It has generally been assumed that these fibers are under tension, but no direct evidence of such a static tension is available. The greatly thickened periosteum which forms the outer wall of the ductus cochlearis is called the *spiral ligament*. Its lower portion forms the attachment of the outer edge of the basilar membrane. The under surface of the basilar membrane is covered by vascular connective tissue. One artery, somewhat larger than the rest, running lengthwise with the basilar membrane, is termed the *vas spirale*. The blood supply of the cochlea is provided by the internal auditory artery, a branch of the basilar artery, which accompanies the auditory nerve through the internal auditory meatus from within the cranium.

The *organ of Corti* is a series of epithelial structures arranged along the inner edge of the basilar membrane (Fig. 113). A *tunnel*, which is composed of two rows of rods, the inner and

outer pillars, or *rods of Corti*, forming a triangle with the basilar membrane beneath them, divides the organ of Corti into an inner and outer portion. The inner rods of Corti stand at the attachment of the basilar membrane to the spiral lamina. The nerve fibers which innervate the outer portion of the organ of Corti pass across the tunnel. On the inner side of the inner rods

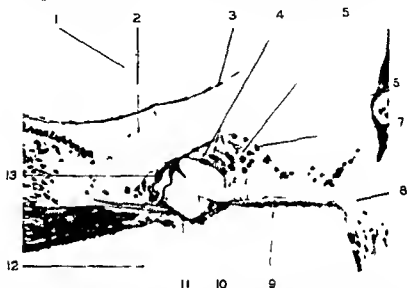


FIG 113 Photomicrograph of the organ of Corti from the first turn of the cochlea of a guinea pig. The human organ of Corti is closely similar. The bending of the rods of Corti and of the basilar membrane is a fixation artefact (Lurie, 1, 2)

- | | |
|-------------------------------|--------------------|
| 1—scala vestibuli | 7—Hensen's cells |
| 2—tectorial membrane | 8—spiral ligament |
| 3—Reissner's membrane | 9—basilar membrane |
| 4—external hair-cells | 10—rod of Corti |
| 5—supporting cells of Deiters | 11—tunnel |
| 6—scala media | 12—scala tympani |
| 13—internal hair-cell | |

is a single row of hair-cells, the *inner hair-cells*, and on the outer sides of the outer rods are three or four rows of smaller *external hair-cells* together with various supporting cells. The terminal fibers of the acoustic nerve end in contact with these hair-cells, which are the ultimate sensory cells of the organ of hearing. Their name is derived from the cilia, or tiny hairs, which pro-

ject from their upper ends into the endolymph of the ductus cochlearis

Above the organ of Corti is a semisolid structure consisting of fine colorless fibers imbedded in a transparent matrix. This *tectorial membrane* is attached at its inner edge to the superior lip of the osseous lamina near the attachment of Reissner's membrane. The tectorial membrane varies considerably in different microscopic preparations, and it is still an open question whether it pre exists in the living state in the form in which it is seen after fixation and preparation for study under the microscope. There is some reason to believe that it may represent a post mortem coagulation or condensation of a much more diffuse colloidal structure or material in the ductus cochlearis (Bowen)

The resonance theory of hearing postulates that different portions of the basilar membrane vibrate selectively in response to different frequencies. With this possibility in view it is of some interest to consider the variations in dimensions of the structures of the cochlea as a function of their distance from the oval window (see p 277)

The cross-section of the canal of the cochlea becomes smaller as we approach the helicotrema, but the change is somewhat irregular. The basilar membrane, on the other hand, is narrowest at the end near the round window and vestibule and becomes progressively and systematically wider toward the helicotrema. Figure 114 presents these facts in diagrammatic form with actual measurements. The tunnel of the organ of Corti also becomes progressively larger. The inner and outer rods near the round window are about 50 microns in length, whereas near the helicotrema they are approximately 85 and 100 microns, respectively. The span of the arch increases from 20 to 85 microns. A group of cells situated to the outer side of the external group of hair-cells are known as *Hensen's cells* (Fig 113), and contain fat globules. The fat globules are absent in the basal coils (at least in adult guinea pigs), appear halfway around the second coil, and show a finely graded increase toward the apex, where their bulk is considerable (Hall

pike, 1) The same arrangement may reasonably be inferred for the corresponding cells in the human organ of Corti, since in other details the microscopic structures of guinea pig and man bear a close resemblance to one another. The spiral ligament decreases in size from the vestibule to the helicotrema, whereas the tectorial membrane increases progressively in size

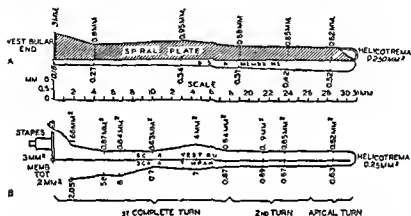


FIG 114 Diagram showing the dimensions of the basilar membrane and of the canals of the human cochlea (Fletcher 1 based on measurements from Wrightson and Keith Courtesy of D Van Nostrand Company Inc)

from basal to apical end of the cochlear canal. These progressive, systematic changes in dimensions are presumably important in the dynamics of the cochlea.

There are approximately 3500 hair cells in the inner row and about 20,000 divided among the three outer rows. The inner hair cells are slightly larger (12 microns) in diameter than the outer hair-cells (8 microns) and the dimensions of each type are constant along the basilar membrane. Both the internal and the external hair-cells are quite evenly spaced along the basilar membrane.

There are between 25,000 and 29,000 ganglion cells in the spiral ganglion of Corti within the modiolus. They are not evenly distributed along the length of the basilar membrane, being more densely congregated in the upper portion of the basal turn and fewest in the upper middle and apical sections. The average numbers per millimeter are lower basal, 934,

upper basal, 1076; lower middle, 971; upper middle and apical, 502 (Guild, 2).

Each inner hair-cell is innervated by one or two nerve-fibers, and each nerve-fiber makes connections with one or two hair-cells (Lorente de Nó, 2). The external hair-cells, however, have multiple innervation. A nerve-fiber may connect with

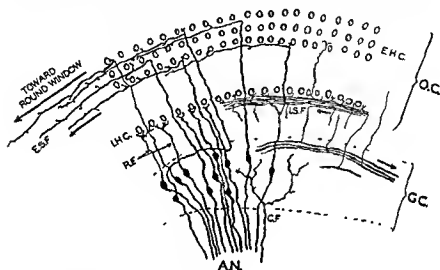


FIG. 115. Diagram of the innervation of the organ of Corti. (After Lorente de Nó, 2)

- OC. — organ of Corti
 - EHC. — external hair-cells
 - ESF. — external spiral fibers, each innervating many external hair-cells
 - ISF. — internal spiral fibers, of unknown function
 - IHC. — internal hair-cells
 - RF. — radial fibers, innervating the internal hair-cells
 - GC. — ganglion of Corti
 - CF. — centrifugal fibers, of unknown function
 - AN. — auditory nerve
- Arrows show the direction of the fibers away from their cell bodies

many external hair-cells, extending over a range of as much as one-half of a turn, and each hair-cell may be connected with several nerve-fibers. The nerve-fibers to the outer rows of cells pass out radially from the spiral ganglion, cross the tunnel of the organ of Corti, and, upon arriving in the outer rows, turn sharply and pass down toward the basal end of the cochlea. Figure 115 illustrates this mode of innervation of the hair-cells.

The anatomical arrangement of the nerve fibers in the auditory nerve and their central connections will be considered separately in Chapters 16 and 18

DYNAMICS OF THE INNER EAR

We have considered the anatomy of the inner ear as it appears under the microscope after death. The problem of how the ear, as a physical system, reacts to pressure waves transmitted to it by way of the footplate of the stapes has not yet been solved in all details. The small size and relative inaccessibility of the cochlea make direct observation difficult. On the other hand, we can apply, with some confidence, certain physical principles, and thereby discover the probable mode of vibration of the basilar membrane and what pattern of nerve impulses the vibration will set up in the auditory nerve.

The bony labyrinth is a practically closed chamber with rigid walls, except for the oval and round windows. The fluid within it is incompressible, and therefore, when the footplate of the stapes vibrates, significant mass movements of the fluid within the labyrinth can occur only by virtue of the yielding of the round window membrane. It is evident from Fig. 102 that slow inward movement of the stapes can cause a flow of perilymph up the scala vestibuli, through the helicotrema, and down the scala tympani to the round window. Figure 105 illustrates an alternative pathway. When the movement of fluid up the scala vestibuli is rapid it will be opposed by the frictional resistance to flow in the narrow scala and by the inertia of the fluid column in the apical turns. This process will generate pressure in the endolymph and hence on Reissner's membrane (which we may assume to be practically flaccid and unresisting) and on the basilar membrane beneath it. The basilar membrane will bulge into the scala tympani, as shown in Fig. 105, and displace the perilymph within it toward the round window. The more rapid the movement, the closer to the round window is the bulge in the basilar membrane.

We shall be able completely to account for the dynamic behavior of the cochlea in response to an acoustic disturbance

only when we shall have succeeded in setting up and solving the differential equations describing the motions of the various parts of the cochlear system and in evaluating the several constants involved. An attempt at such a set of equations is presented in Appendix II. Here, however, we may consider the nature of certain principles which make it reasonable to suppose that the basilar membrane responds at different places to different frequencies.

Two principal factors operate to place the disturbance of the basilar membrane closer to the round window when the frequency of stimulation is raised. (1) The basilar membrane is broadest near the helicotrema and narrowest near the round window. If the fibers of the membrane are under tension, their varying elasticity will make the longer fibers more susceptible to movement by low frequencies. The strings of a piano exhibit a crudely analogous effect. The shorter fibers will be moved most easily by high tones. (2) The mass of the total amount of fluid moved will be smaller when the disturbance is nearer to the round window. Now, in a mechanical system, the natural frequency is higher, the smaller the mass of the system. Consequently, high frequencies will tend to activate the ear in such a way as to move a small mass. Just what mass will be most readily displaced by a given frequency will depend upon the additional factors of the stiffness and resistance involved, but the general principle is clear: less cochlear fluid will be set in motion by a high than by a low frequency.

Roaf sums up the dynamics of the cochlea as follows: "It is evident that the impedance due to the mass and friction of the perilymph will tend to produce greater differences of pressure at the narrower end of the basilar membrane with rapid changes, whilst slower changes will cause lesser differences, so that the basilar membrane will be moved at a wider part."

According to these principles, aided presumably by minor factors such as variations in the physical constants of the organ of Corti, the basilar membrane will vibrate selectively at one part or another according to the frequency of the sound. This selective vibration is the fundamental physical basis of the

analysis of sound by the cochlea. Direct evidence of such 'tuning' of the cochlea and the locations of the regions of maximal sensitivity to particular frequencies will be presented in Chapter 15.

Evidence that a change in the physical constants of the inner ear alters the perceived pitch of a tone is presented by Békésy (4). He observed that when the veins of the neck are compressed, so that the veins and capillaries of the head become engorged with blood, the pitch of a tone may diminish by an amount corresponding to a reduction of 2 per cent in frequency. The effect is most evident with low tones of moderate intensity. Distention of the small veins and capillaries presumably alters the stiffness and mass of the vibrating structures of the inner ear sufficiently to modify the pattern of vibration of the basilar membrane.

It should be emphasized here that the preceding discussion should not be interpreted as implying a simple resonance theory of hearing. True, the cochlea *behaves as if* the basilar membrane were composed of a row of tuned resonators, in the sense that a maximum of vibration occurs at a given place for a given frequency, but the physical principles by which this *apparent tuning* is achieved are far more complex than those involved in simple resonant systems. For one thing the apparently highly damped state of the cochlea rules out the simple picture of a row of resonators and requires that we invoke alternative concepts, such as those suggested in Appendix II.

TRAVELING WAVES ON THE BASILAR MEMBRANE

The brief outline of the dynamics of the cochlea presented above is based upon inference rather than upon direct observation. It has not yet proved technically possible to observe the basilar membrane in vibration with sufficient accuracy to determine directly its pattern of vibration either in response to steady tones or to sudden impulses. In principle, such observations might be carried out and the pattern of vibration determined if the basilar membrane could be viewed under stroboscopic illumination. The efforts which have been made do little

more than demonstrate the difficulty of the undertaking. The study of large scale physical models, which attempt to reproduce the conditions in the cochlea, is open to the fundamental objection that assumptions must always be made as to the correspondence between the physical constants of the model and those of the ear itself. Obviously, until the actual physical constants of the ear are better known than they are at present, the conclusions drawn from the study of models are no better than the assumptions which enter into their construction.

In spite of this difficulty, certain observations by Bekesy (15, 2) upon a model of the inner ear are of great interest, for they indicate certain features of the dynamics of such a system which are not directly evident from the analysis previously presented. They show that when the stapes is suddenly displaced all the basilar membrane does not move simultaneously, as we might



Fig. 116 Diagram of a traveling wave set up on the basilar membrane by outward movement of the stapes (After Bekesy 15)

expect, but a wave sweeps progressively along it, like the wave which travels along a slack rope that has been given a sudden shake.

Bekesy reports that under stroboscopic illumination it can be seen that a momentary aperiodic displacement of the stapes causes the fluid in the neighborhood of the stapes to move with it like a piston, so that up to the region where an eddy is generated when a strong steady tone of 1000 cycles is employed, the basilar membrane momentarily bulges up, while the region in the neighborhood of the helicotrema remains quiet. This behavior is illustrated by the heavy line in Fig 116. Shortly thereafter the region in the neighborhood of the stapes swings back aperiodically to its position of rest, while, at the other end, as shown by dotted lines in the figure, a flat traveling wave is generated which spreads completely up to the helicotrema. The

sudden bulging up of the basilar membrane throughout the region up to that which normally responds maximally to 1000 cycles indicates that the velocity of propagation of the traveling wave in the neighborhood of the stapes exceeds that in the more distant region

If one allows the stapes of the model to execute a single vibration, such as would result from a momentary alteration of pressure in the auditory meatus, the first half of the membrane follows exactly the vibration of the stapes, while in the neighborhood of the helicotrema two or three wave peaks, corresponding to highly damped traveling waves, may be seen

THE VELOCITY OF THE TRAVELING WAVES

Békésy does not hesitate to carry over to the human ear the conclusions drawn from the observation of his model, nor are we entirely without evidence to justify his confidence. The notion of a form of vibration of the basilar membrane which consists of a progressive series of traveling waves running along the membrane enables us to account for the temporal dispersion of the nerve impulses in the auditory nerve which are set up by stimulation by a sudden sound. The pattern of the nerve impulses is considered in Chapter 16, but, because of the apparently intimate relation between their temporal dispersion and the mode of vibration of the basilar membrane, certain features of neural activity must be examined at this point

When the ear is stimulated by an abrupt sound wave, such as a click, the resulting nerve impulses do not all appear simultaneously with one another in the auditory nerve. Some appear after considerable delay. The earliest are those generated near the middle of the basilar membrane. They are the impulses which are masked most effectively by tones between 2000 and 2500 cycles. The difference in latency between impulses generated at this point and those initiated near the helicotrema is as much as 1.5 to 2.0 msec. If we take 30 mm as the length of the basilar membrane and the difference in latency between the two groups of impulses as 1.5 msec, the speed of propagation of the traveling wave along the upper half of the cochlea turns out

to be approximately 10 meters per second. This figure is, of course, only an approximation, but it indicates the order of magnitude involved. Furthermore, it is almost certain that the speed of propagation over the basal half of the cochlea is considerably greater than this, since the earliest group of impulses generated near the middle of the basilar membrane appears after a latency which may be as brief as 0.7 msec. This fact indicates a velocity of the traveling wave of at least 20 to 30 meters per second over this first portion of the basilar membrane. In all probability, there is a gradient of velocity from one end of the membrane to the other.

Another type of evidence for a slow traveling wave in the cochlea is presented by Bekésy (15). When a click and a steady tone are presented simultaneously to the ear, the click is partially masked by the tone. A combination of click and tone can be presented to one ear of a human subject, while the other ear is stimulated simultaneously by a click alone. The intensities of the two clicks may then be adjusted so that they appear equal in loudness. Under these conditions the observer hears a click which seems to come from a source situated to the side of the head—the side toward the ear stimulated by click plus tone. The effect is more pronounced the lower the frequency of the masking tone. Apparently the *low* tone masks the *late* component of the excitation due to the click, so that the click appears to occur earlier in time. Bekésy measured the interval by which the unmasked click must be advanced, in time, in order that the sound image should be referred to the center of the head (see Chapter 6), or in order that it should be physiologically simultaneous with the masked click. When a masking tone of 800 cycles was used, the difference was scarcely measurable, but with a 100-cycle tone it was 1.3 msec. He concluded that the apparent advance in time due to masking depended upon the elimination, by the low pitched masking tone, of the later components of the nerve response, which arise when the traveling wave reaches the apical end of the basilar membrane.

A velocity of 10 or 20 meters per second is far less than the

velocity of sound waves in water, or even in air. This relatively slow velocity is not a pertinent objection to the hypothesis of a traveling wave, however, since the problem is not one of propagation of sound waves in an infinite extent of homogeneous fluid, but of the propagation of a wave along a tube having an elastic wall. The velocity of propagation of a wave of pressure in such a system is much less than the velocity of sound and depends upon the elasticity, thickness, and other properties of the wall of the tube (cf Appendix II). An interesting and analogous case of propagation of a disturbance in an elastic tube is the transmission of the pulse wave in an artery. With hardening of the arteries, the velocity of the pulse wave is increased (C J Wiggers).

ADDITIONAL FEATURES OF THE TRAVELING WAVE

Let us now consider the probable relation between the form of a click, its acoustic spectrum, the region of the basilar membrane maximally stimulated by it, and the manner in which the stimulation travels along the membrane from the round window to the helicotrema. Various aspects of this total problem have been treated in other chapters, but it should be instructive at this point to review the picture. In so doing we shall see how it is possible for a stimulus comprising a continuous spectrum of sound-energy to send a wave of disturbance running along the basilar membrane in such a way as to set up a distribution of excitation which reflects the distribution of energy in the sound spectrum.

These notions are illustrated by the schematic diagrams in Fig 117. Click *A* is a dull click whose pressure wave rises and falls rather gradually. To the listener click *A* sounds like a dull thud. The distribution of energy among the frequencies composing the spectrum of this click shows a maximum near the low frequency end of the scale. In contrast click *B* is a sharp click whose pressure-change is abrupt. Click *B* sounds like a sharp crack. The spectral distribution for this type of click is peaked in the region of high frequencies. Now, each

of these clicks initiates a movement of the eardrum, and hence of the stapes, which has essentially the form of the pressure wave of the click. Movement of the stapes tends to compress the fluid in the scala vestibuli, but the pressure is relieved by a bulging of the basilar membrane into the scala tympani, while the pressure in the scala tympani is relieved by a bulging of the round window membrane. The wave of pressure tending

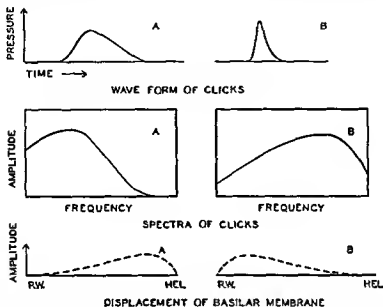


FIG. 117 The three pairs of curves represent schematically the wave form the corresponding sound spectra and the amplitude of displacement along the basilar membrane of a dull click (A) and of a sharp click (B)

to bend the basilar membrane begins near the round window and travels toward the helicotrema at a speed of 10 to 30 meters per second. The membrane executes a whip-like motion, and the important question becomes that of determining how the motion differs when we 'crack the whip' with a dull as against a sharp click. Because of the factors of mass, resistance, and elasticity in the cochlea the sharp click will move, with relative ease, the part of the membrane near the stapes, but its effect will rapidly diminish as the wave moves farther away. The traveling wave of the dull click, on the other hand, will be rela

tively more effective near the helicotrema in producing a displacement of the membrane. Hence, it is possible to picture the relative amplitude of motion of the basilar membrane at various points along its length, as shown in Fig 117.

These curves, showing the relative amplitude of the traveling wave at different distances from the round window, reflect the essential features of the curves representing the spectrum of the clicks. When the maximum of the spectrum is in the region of low frequencies, the maximum of the disturbance on the basilar membrane is near the helicotrema. A spectrum dominated by high frequencies produces a maximum of displacement near the round window. This correspondence of spectrum to pattern of stimulation shows that, in a sense, the ear behaves essentially as an analyzer, even for discrete clicks, and it explains why some clicks sound sharp and high pitched and others sound dull and low pitched (cf Chapter 3).

TRAVELING WAVES IN RESPONSE TO STEADY TONES

When we apply the concept of the traveling wave to the motion of the basilar membrane in response to a steady tone, we find that the various parts of the basilar membrane do not move up and down in the same phase but that the part near the stapes leads, in phase, the part closer to the helicotrema. Fletcher (2) applied these principles in a theoretical study of the mechanics of the cochlea and deduced a similar type of motion for the basilar membrane. He was forced to make various assumptions concerning the tension and other constants of the basilar membrane, but he pointed out that, according to almost any reasonable assumption one can make, the part of the membrane next to the oval window leads in phase of vibration the motion of the part near the helicotrema. In accordance with this view, if motion pictures were to be taken with exposures $T/8$ seconds apart, where T is the period for one complete cycle, we should obtain a series of pictures like those shown in Fig 118.

This picture in no way conflicts with the idea of a region of maximal amplitude of vibration for a given frequency. The

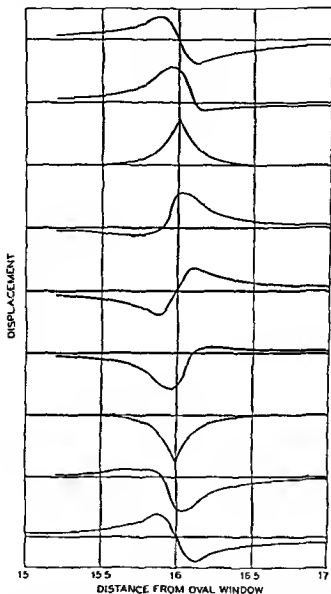


FIG 118 Diagrams of the pattern of vibration of the basilar membrane during one complete cycle of a steady tone. The nine heavy lines represent the instantaneous patterns of the membrane at successive intervals of one eighth of a cycle of the tone. Each wave of vibration passes progressively along the membrane away from the oval window. The amplitude of vibration is greatest at 16 mm from the oval window (Fletcher, 2)

figure actually illustrates maximal amplitude at the distance of 16 mm from the oval window—the situation which would be produced by a tone of about 2000 cycles

Békésy (2) has pointed out that a motion of the basilar membrane like that shown in Fig 116 would tend to produce small vortices, or eddies, in the liquid above the position of maximal stimulation. When the exciting tones were loud, he observed such eddies, both in his models of the ear and in dissected human ears. He believes that the pressure of these eddies against the membrane causes stimulation of the nerve endings. He points out, furthermore, that such an eddy would produce a movement of the liquid in the semicircular canals and affect the sense of balance in such a way as to cause the listener to tilt his head toward the ear receiving the sound. Precisely this effect appears to occur in response to very loud tones. The presence of these eddies at high sound intensities need not, however, account for the stimulation of the nerve endings of the auditory fibers. At low intensities, such eddies probably do not occur and therefore stimulation must depend upon mechanical distortion of the hair cells, due to bending of the basilar membrane, rather than upon a hydraulic pressure generated by vortices (see p 343). (The possibility of stimulation by a pressure gradient in the fluid of the cochlea has been pointed out by Reboul (see Appendix II) but this effect is different from the pressure generated by vortices.)

THE DAMPING OF THE BASILAR MEMBRANE

An important aspect of the basilar membrane as a vibrating structure is its damping factor. The damping factor tells us how rapidly the vibrations die out after the stimulus ceases. The impossibility, however, of considering the basilar membrane as a separate structure apart from the fluid which surrounds it should be at once apparent. In fact, any attempt to discover the damping factor of the basilar membrane itself is subject to difficulties arising from the fact that the membrane is closely coupled to the rest of the auditory mechanism. Hence, the rate of decay in the oscillations of the entire auditory sys-

tem when a tone is turned off may or may not correspond to the rate of decay attributable to the inner ear alone. Furthermore, measurements of the damping of the ear in terms of the persistence of an auditory sensation may be vitiated by the factor of persistence in the central nervous system (see p 223)

Considering the auditory mechanism *as a whole*, several efforts to determine its time-constant, or damping factor, have yielded values ranging from 33 to 200 msec. A representative mean value for this time-constant is 50 msec (Lichte). This value means that the amplitude of the oscillations of the ear as a whole following the cessation of a tone falls to $1/2^{718}$ of the initial value in the time of 50 msec (cf p 263)

It is probable, however, that if we consider the inner ear separately, the viscosity of the fluid in the cochlea renders the basilar membrane even more highly damped. One effect of this large damping is to dull the selective response of the membrane in such a way that a single tone activates an extensive area. We have already seen (Fig 93, p 216) that a single tone may mask other tones throughout the audible range, and we have interpreted the curves for masking as representing the extent of the disturbance attributable to a single frequency. We shall see later (p 330) that there is no evidence in the electrical activity of the cochlea of any significant persistence of vibration of the basilar membrane following the interruption of a tone. Everything considered, then, we must conclude that the inner ear is highly damped and that this damping impairs its resolving power in the analysis of sound waves.

CHAPTER 11

DEAFNESS AND BONE CONDUCTION

IMPAIRMENT of hearing may result from three main factors, operating singly or in various combinations. The first factor is the failure of transmission of the physical sound waves to the inner ear. This type of deafness is frequently designated as *transmission deafness*, and also, since it usually depends upon some abnormality of the drum or middle ear, as 'middle ear deafness'. The second factor is damage to the sensory cells or to the nerve fibers and nerve centers immediately connected with them. This damage produces what has been variously designated as *nerve deafness* or 'perception deafness'. Nerve deafness is not always due to degeneration of the auditory nerve, but may result from degeneration of the hair-cells of the organ of Corti. Damage to the hair cells is, however, physiologically equivalent to damage to the nerve. The third type of deafness is the so-called *central deafness*, and includes conditions in which impulses reach the central nervous system along the auditory tracts, but in which the patient is unable to recognize them or give them their usual meanings. This third type depends upon abnormalities or dysfunction of the higher nervous centers, and will not be considered further in this book.

The distinction between transmission-deafness and nerve deafness is of fundamental practical importance, since, as long as the essential sensory apparatus and its nerve supply remain intact, there is always the possibility that means may be found to deliver sound vibrations to that sense-organ at sufficient intensity to stimulate it, and so give rise to useful hearing. Once the sense-organ or nerve is destroyed, however, there is no hope of regeneration or of attaining through any other nervous pathway the differential sensitivity to sound waves which is the necessary basis for the recognition of speech and music. The effect of nerve deafness on the perceived loudness of sounds is discussed in Chapter 4 (pp 131-136).

TRANSMISSION DEAFNESS

The simplest and most obvious form of transmission deafness is mechanical closure of the external canal. This may sometimes occur from the gradual accumulation of wax, and lead to a hearing loss of many decibels. A similar loss may be produced by the accumulation within the middle ear of solid or semisolid material, such as pus or exudate from an inflammatory process. The damping effect of such material on the transmission of sound waves may be very large. The simple damping effect of the material is, however, usually complicated by the effects of the increased or decreased pressure within the middle ear.

The effect of difference of pressure on the two sides of the tympanic membrane is experienced in pure form when we are subjected to rapid changes of atmospheric pressure, as in rapidly moving elevators or airplanes. This effect, and the subjective sensations which accompany it, are matters of common experience, and a temporary deafness, particularly for low tones, quite commonly occurs. Relief is afforded by swallowing, which opens the Eustachian tube and allows equalization of pressure on the two sides of the tympanic membrane.

During an infection of the middle ear, the Eustachian tube is closed by the inflammatory process, and oxygen is gradually absorbed from the air which has been trapped in the middle ear. The tympanic membrane is then retracted, owing to the diminished pressure in the middle ear. Fluid is later exuded during the acute processes of inflammation and is finally reabsorbed. The result of these processes is first to increase and then, if the drum has not ruptured, to diminish pressure in the middle ear and cause an acute retraction of the tympanic membrane. The distention and retraction are both accompanied by a low tone deafness. The retraction may be relieved by 'blowing out' the ears. In the presence of inflammation of the Eustachian tube and middle ear, relief may require cannulation of the Eustachian tube. Such treatment is often highly desirable as a prophylactic measure, in order to avoid formation of permanent adhesions which would hold the drum in its retracted position.

During the earlier stages of acute infection, when pus accumulates in the middle ear, the tympanic membrane bulges outward, and may rupture spontaneously unless relieved by surgical intervention. Surgical perforation is desirable under these conditions, since it allows the pus to escape through a small opening in the drum, which almost invariably heals following recovery from the infection. If the drum is not pierced, long continued internal pressure may shut off the blood supply from portions of the tympanic membrane and cause widespread necrosis, so that, after spontaneous rupture has finally occurred, repair may not be complete and may leave a permanent opening in the drum. The degree of permanent loss of hearing following such a condition is variable. Perforation of the drum *per se* causes very little loss of sensitivity (Lorente de No, 1, and see p 253). Middle ear deafness resulting from infection usually depends upon thickening of the drum and the formation of permanent adhesions to the ossicles. An extensive deficiency of the tympanic membrane increases such 'middle-ear' deafness. This common type of deafness, well recognized clinically, is characterized by loss of hearing for low and sometimes for middle frequencies, and usually, but not always, retention of sensitivity for high tones. It corresponds rather closely to the condition realized, physiologically, during maximal contraction of the inner ear muscles, and is to be interpreted in the same way, that is to say, as a restriction imposed upon the free vibration of the transmission mechanism of the middle ear.

When, as a result of severe infection, the tympanic membrane, and also the ossicles, are completely lost, hearing may still be possible. The hearing loss in these cases involves high as well as low tones (Fig 104, p 253) and is sometimes very severe. It depends upon the exact details of the physical changes which have occurred.

Fixation of the stapes in the oval window may occur in certain pathological conditions, notably otosclerosis. Without going into detail concerning this important, but obscure, condition, which usually involves a progressive degeneration of some of the hair-cells in the organ of Corti (Lurie, 1), we may

note that fixation of the stapes would be expected, on physical principles, to cause a severe low tone loss as well as some loss throughout the entire range. This is precisely what usually occurs.

We cannot be dogmatic about the degree and type of hearing loss to be expected from any particular abnormality in the middle ear. Slight differences in the location of an adhesion, or in its rigidity, may profoundly modify its influence upon the movements of the ossicles. Although it is true, as a general rule, that adhesions and other abnormalities in the middle ear tend to depress low tones more than high, it is nevertheless well recognized that high tones may be involved in transmission-deafness, and, on the other hand, considerable pathology may exist without measurable loss of hearing. This latter point is illustrated by the post mortem studies of Polvogt on the ears of sixty three patients whose hearing had been tested and found to be normal shortly before death. He found that bands of embryological or fibrous tissue in the niche of the round window may have no effect on the acuity of hearing. We must assume that such bands do not necessarily interfere with the essential movements of the stapes. Marked pathological changes of the tympanic membrane may also exist without causing any noticeable impairment of the hearing. The drum may even be extremely retracted and adherent to the mucous membrane over the promontory. On the other hand, nothing was found in any of Polvogt's cases which would interfere with free movement of the head of the malleus and incus, or with the normal functioning of the Eustachian tube. Also the annular ligament which surrounds the footplate of the stapes was normal in all cases.

BONE CONDUCTION

Even when air-conduction is completely abolished by some pathological process, it is possible to hear vibrations which are effectively transmitted to the bones of the skull. The stem of a vibrating tuning fork applied to the mastoid process is a simple method of obtaining such transmission. Tests based upon this procedure are employed for the differentiation between deaf

ness due to loss of air conduction and deafness due to damage or degeneration of the sense-organ of the inner ear (American Otological Society Symposium) Special *bone-conduction receivers* have been designed for use with standard audiometers to transform alternating electric currents into mechanical vibration of the skull. They correspond in principle to the familiar telephone receiver which generates sound waves. The audiometer with its bone conduction receiver is calibrated at various frequencies in terms of the threshold of normal ears, and the loss of sensitivity of a given ear, as a function of frequency, may thus be measured quantitatively (see p. 64). As long as the threshold for bone-conduction remains normal or nearly so, we may safely infer that the sense-organ essential for hearing remains normal. If bone-conduction is impaired the inner ear *may* be damaged, but not necessarily (see p. 295).

It is obvious that bone-conduction may play some small part in the normal transmission of ordinary sound vibrations to the inner ear, but the efficiency of transfer of energy from air to bone is so low that it is usually negligible. Nevertheless, in determinations of the sensitivity of a partially deafened ear, the conduction of sound to the opposite normal ear by bone conduction may become very important. The threshold for such transmission to the opposite ear is some 50 or 60 db below the threshold for air conduction. It is therefore impossible to test thresholds more depressed than this, unless some means are employed to eliminate the hearing of the normal ear. This elimination may be achieved by masking it with some other sound, usually a rough noise (American Otological Society Symposium). Masking prevents the normal ear from detecting the faint sound in question, and does not appreciably affect the threshold of hearing for the opposite ear (see Chapter 8) unless the masking noise is itself carried back, by bone-conduction, to the ear which is being tested.

ABSOLUTE THRESHOLD FOR BONE CONDUCTION

No measurements are available for the energy required to attain the threshold for bone-conduction. Measurements of

the threshold in terms of amplitude of vibration show that the movement necessary to give rise to hearing is extremely small. Knudsen and Jones give 27×10^{-8} cm as the threshold amplitude for an aluminum rod applied to the mastoid process when vibrating at 1024 cycles. Békésy (12) measured the actual movement of the forehead in the immediate neighborhood of such a vibrating rod and found its amplitude to be only a few per cent of the movement of the rod. Correcting for this factor, he gives a figure of about 3.5×10^{-8} cm movement of the skull for threshold at 800 cycles. The threshold is lowered to 5×10^{-10} cm by closing the external canal. This figure is almost identical with the minimal threshold amplitude of movement of the eardrum itself determined by a vibrating rod in direct contact with the drum (Wilska, see Fig 18, p 56). The relation to frequency of the threshold amplitude for bone-conduction has been determined directly only for frequencies below 1024, where the relation seems to be similar to that for air-conduction.

MECHANISM OF BONE CONDUCTION

Experimental evidence (Békésy, 12) appears to indicate that both air-conduction and bone-conduction ultimately cause similar movements of the endolymphatic fluid and of the basilar membrane in the cochlea. The air borne vibrations arrive by way of the ossicles, whereas vibrations of the skull result in compression of the canals of the inner ear, including the labyrinth. Such compression increases the pressure in the scala vestibuli more than in the scala tympani because the round window, in communication with the scala tympani, is more elastic than the oval window, which is closed by the footplate of the stapes (Fig 119 B). Still more important, according to Békésy, is the fact that the semicircular canals communicate with the scala vestibuli and, when they are compressed, fluid is forced into the scala vestibuli (Fig 119 C). By a series of ingenious experiments in which bone conducted vibrations were compensated by equal and opposite vibrations delivered to the stapes from air borne waves and in which the freedom of movement of the stapes was altered by raising and lowering the air pressure on

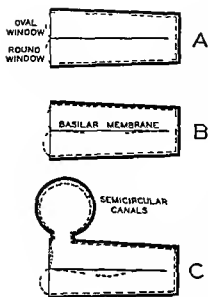


FIG 119 Showing how compression of the inner ear by bone-conducted sound waves leads to movement of the basilar membrane. The dotted lines indicate the sizes of the various chambers and the positions of the various membranes during compression by a sound wave in the skull (Békésy, 12)

A Hypothetical case of symmetrical compression of the cochlea and equal yielding of the membranes of the oval and round windows. No movement of the basilar membrane would occur.

B The round window actually yields more than the oval window to equal pressures. The basilar membrane is moved slightly toward the scala tympani.

C The semicircular canals are compressed as well as the cochlea. Fluid forced from the semicircular canals into the scala vestibuli causes greater movement of the basilar membrane into the scala tympani.

the tympanic membrane, Békésy demonstrated the existence of this type of compression. It constitutes the most important element of the mechanism of hearing by bone-conduction when the external canal is open.

When an observer listens to a tone by bone-conduction and closes the external auditory canal, the tone increases in loudness. The vibration of the skull then compresses the air in the external canal and the observer virtually hears by the usual mechanism for air conduction. The loudness may then be diminished by increasing the air pressure in the external canal, thereby tensing the tympanic membrane and the ligament of the footplate of the stapes, just as in ordinary air-conduction. On the other hand, when the external canal is open, tensing of the tympanic membrane and ossicular chain causes an *increase* in loudness of a bone-conducted tone because it fixes the stapes more rigidly and prevents loss of pressure from the scala vestibuli by way of the oval window. Compression of the cavities of the inner ear and labyrinth

is here the dominant factor in producing vibration of the basilar membrane

The conclusion that an osseous rather than an osseo-tympanic pathway is most important for the transmission of bone-conducted vibrations to the inner ear is confirmed by the animal experiments of Guild (3) and of Wever and Bray (7). The electrical activity of the cochlea in response to air-conducted and to bone-conducted vibrations was measured and then the ossicular chain was interrupted at the incudostapedial joint. Air conduction was diminished by 50 to 60 db, but bone conduction was not reduced by more than 5 or 10 db.

In human ears a particular osseous pathway is of special importance. This pathway is the bony trabeculae of the subaditus region. These bony structures are almost directly opposite the opening of the scala vestibuli into the vestibule. The importance of these trabeculae is shown by the demonstration in post mortem sections (Guild, 3) of fractures of these trabeculae in a number of individuals whose hearing by bone conduction had been found to be markedly impaired. These fractures explain the otherwise paradoxical situation of a person whose hearing by air conduction is normal, but who has impaired bone-conduction. All the cases in Guild's series which showed this combination of normal air conduction and impaired bone conduction proved to have fractures of *all* the trabeculae in the subaditus region.

CHAPTER 12

PRINCIPLES OF NEUROPHYSIOLOGY

FROM a consideration of the ear as a mechanical system we turn now to the study of its behavior as a neuromechanical transducer capable of transforming acoustic energy into nerve impulses. In order properly to understand this function of the ear, it is advantageous for us first to review certain fundamental principles of neurophysiology. The activity of nerves reveals itself most readily by the electrical phenomena which accompany it, and much of the recent development of the physiology of audition has been due to the application of the methods of electrophysiology to the organ of hearing and to its associated nervous pathways. In this chapter we shall examine the nature of the electric potentials generated in living cells.

ELECTRICAL POLARIZATION OF CELLS

Certain electrical properties are exhibited by all living cells. Other properties or activities are limited to special types of cells whose functions are highly developed and highly specific. All cells and tissue fluids contain electrolytes in solution and are capable of conducting electricity. We measure this property in terms of electrical resistance. Certain limitations are imposed on the free movement of ions, partly by the internal structure of protoplasm, partly by the boundary membranes of the cells, and partly by the organization of cells into definite structures like the sheaths of nerve trunks or the dura mater of the brain, whose resistance is great as compared with tissue fluids or protoplasm.

As far as we know, all cells are electrically polarized, as between the inside of the cell and the external medium. This statement means that if one electrode is placed on the outer surface of a cell and another brought effectively in contact with the protoplasm, a difference of electric potential appears between the two electrodes. This difference of potential can be reduced

by injury and abolished by death. It is in part a direct physicochemical expression of differences of composition between the interior of a cell and its surroundings, and in part an expression of the dynamic activity involved in maintaining these differences. We are ignorant as to the precise mechanisms involved in the generation of these bioelectric potentials, but many of the important facts are well described by the *membrane hypothesis*, which regards the cell as a solution, different in composition from the surrounding medium, and separated from it by a semi-permeable membrane. The difference of potential which exists across this membrane was first described by Helmholtz as a

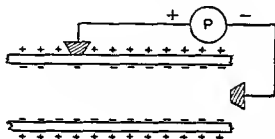


FIG. 120 Diagram of the electrical polarization of a cell membrane. One electrode is applied to an injured end of the cell and the other to an uninjured region. The polarization is measured by the potentiometer, *P*.

double layer of ions—the positive charges outside and the negative charges inside the membrane. This picture has, for decades, been the starting point of electrophysiological theory.

When a cell is injured, the surrounding membrane may be partially interrupted or destroyed, or it may be rendered more completely permeable. The positive and negative charges, formerly separated by the membrane, can then unite, and the surface is depolarized. An electrode placed in contact with this region is effectively in contact with the interior of the cell (Fig. 120), and the difference of potential recorded between such an electrode and one placed on an uninjured portion of the surface of the same cell measures the degree of polarization of that cell. Such a difference of potential is often spoken of as an *injury potential*, since injury is required to penetrate the membrane at some point in order to make the measurement.

It should be clearly recognized, however, that the potential is not generated by the injury, but by the part of the cell which remains uninjured. The injury is simply an unfortunate necessity in gaining access to the interior of the cell. As long as the cell is completely surrounded by its semipermeable membrane, we cannot measure the potential between inside and out. All that we can ever observe by electrical measurements is a difference of potential between two points.

Changes in this physiological polarization are probably associated with many forms of activity, including neural conduction and muscular contraction, but it has been difficult to analyze and measure the changes of polarization on account of the complications introduced by injury. Even when we burn or crush a piece of tissue, the cells may at once begin to heal to rebuild their semipermeable membranes, and to check the diffusion of their contents into the surrounding fluids. To the extent that they succeed, they defeat our experimental purposes. Even the insertion of microelectrodes into the interior of cells does not always overcome this difficulty, for, unless the electrode enters a fluid vacuole in the protoplasm, this same process of repair will take place. If the electrode does enter a vacuole, we face the probable polarization of the boundary surface between the vacuole and the surrounding protoplasm. Difficulties and uncertainties of this sort have kept changes of polarization a topic of interesting controversy for many years.

DISTORTION POTENTIALS

Two fundamentally different types of transient electrical changes may be produced by cells as the result of external stimulation. In the first of these, the cell plays a passive role and simply transforms mechanical, or other incident energy, into electrical effects which we designate as *distortion potentials*. The magnitude of these potentials is a function of the amount of distortion produced. An example is the wave of electric potential which accompanies the mechanical wave set up in the long plant cell, *Nitella* by an abrupt mechanical stimulation (Osterhout and Hill).

There are three general types of physical processes which might account for distortion-potentials as we observe them. (1) The mechanical movement or distortion of any charged or polarized structure may generate an electric potential according to the same principles that underlie the operation of a condenser microphone: a change in the distance between two charged plates or membranes produces a change of potential. (2) The mechanical changes may alter electrical resistance, and so, indirectly, current-flow and potential. The 'stretch-effect' in muscle, described by Einthoven, is probably to be explained by this type of process. The principle here corresponds to that

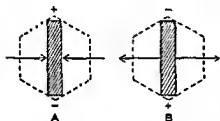


FIG 121. An example of the piezo-electric effect. The shaded area represents the cross-section of a plate cut from a hexagonal quartz crystal, whose original cross-sectional outline is indicated by the broken lines. When mechanical force is applied, as shown by the arrows in *A*, to the faces of the plate, an electric potential-difference appears between the edges. If the polarity of the force is reversed, as in *B*, that is to say, if the force is a 'traction' instead of a pressure, the polarity of the potential-difference is reversed.

of the ordinary carbon microphone or telephone transmitter. Finally, (3) it is quite possible that mechanical distortion of a cell, with the generation of mechanical stresses and strains in a structure containing oriented molecules, may generate differences of potential in a manner analogous to the familiar *piezo-electric effect* in certain inorganic crystals such as quartz. This is the principle underlying the crystal microphone: stress on a crystalline structure sets up a difference of potential along certain

axes. The piezoelectric effect in a quartz plate is illustrated in Fig. 121, but it is worth noting that the term 'piezoelectric' need not be confined to such crystalline structures, since its definition is such as to include all electric potentials generated by the application of mechanical pressure. Effects of this type are of particular concern in our study of the ear, for it appears that the hair-cells of the organ of Corti produce a potential (Chapter 13) in accordance with the principle of the piezoelectric effect.

It is also important to note that in the piezoelectric effect, as in distortion potentials in general, the potential generated is essentially proportional to the mechanical distorting force

ACTION POTENTIALS AND THE ALL OR NONE LAW

An entirely different type of electrical effect in response to stimulation is the *action potential*, the energy for which is contributed by the cell itself and not by the stimulus. In direct contrast to distortion potentials, the action potential is *all-or-none* in character. The stimulus serves merely as a trigger to start the reaction. The potential generated is not a function of the strength of the stimulus but depends entirely upon the nature and the immediate condition of the cell which generates it. The phenomenon is transient in character and forms part of a physicochemical disturbance which when initiated at a localized point, spreads over the whole of the cell. This propagated disturbance is actually the nerve impulse. It may be conceived, according to the generally accepted membrane hypothesis, as a wave of increased permeability and depolarization which sweeps over the entire polarized membrane. The external stimulus serves only to start this process at one point, and thereafter the wave is self propagating. The active region presumably excites the neighboring inactive region by means of the *local bioelectric current* which flows externally from the (polarized) inactive region to the (depolarized) active region exactly as the injury current flows from an uninjured to an injured area (Fig. 122). After from one to several milliseconds the normal semipermeable state is restored by a spontaneous process of recovery and repair.

Since the energy for this action-current, or action potential, comes from the tissue, and the external stimulus serves only as a trigger to set it off by upsetting the equilibrium in a meta stable system, it is not surprising that the nerve impulse and its action potential are *all-or-none* in character. The magnitude of the potential, like the amount of chemical action and heat production associated with the impulse, is not a function of the strength of the stimulus. The stimulus either excites a cell

or fails to excite. The response of a nerve-trunk as a whole may be graded by the excitation of few or many fibers, but, for single nerve-fibers, no gradation of response occurs with changes in the strength of stimulation.

Following a response of the all-or-none type a cell is inexcitable for a brief period of time. This interval is known as the *absolute refractory period*, and occupies the first part of the *recovery period*. Recovery is not completed during the absolute refractory period but continues during the ensuing *relative refractory period*. During this second period the cell may be

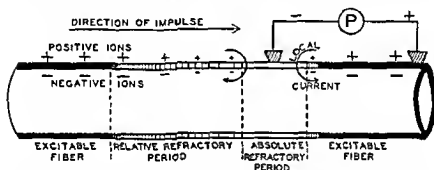


FIG 122. Diagram illustrating the membrane-theory of conduction of the nerve impulse. The polarized semipermeable membrane (solid outline) becomes depolarized and permeable in the active region. The current flow in the local bioelectric circuits, represented by the curved arrows, depolarizes the region in advance of the active zone and thus extends the region of activity. In the region of recovery the nerve is temporarily refractory. A potentiometer, *P*, connected to active and inactive regions registers the relative electrical negativity of the active region.

excited again, but a stronger stimulus is required to reach threshold and evoke a response; and the action-potential is smaller than it is when the cell is fully recovered. We may compare the recovery process to the recharging of a storage battery or an electric condenser.

When stimulation is repeated at a temporal interval so brief that each impulse is set up in the relative refractory period of its predecessor, the successive action-potentials become smaller and smaller, until a steady state is reached at which the processes of recovery and restitution just balance the dissipation of energy in successive impulses. The higher the frequency of

stimulation, the lower is this equilibrium level to which the size of the action potential sinks. This process of *equilibration*—the attainment of a dynamic equilibrium between restoration and dissipation—is a type of fatigue. It is well illustrated in the auditory nerve (Chapter 16), and is characteristic, in general, of the active, all-or none type of response. It should be clear from the above description that the magnitude of the electric response of nerve or muscle is not invariable, although the all or none law is often misinterpreted in this sense. Refractory period, equilibration and fatigue, all of which are characteristic of the all-or none type of response, are not found in the passive types of reaction described as distortion potentials.

An interesting situation in regard to the all or none law is presented by the chemical activation of smooth muscle (Cannon and Rosenblueth). Nerve impulses which are all or none in character liberate, at the nerve-endings, chemical substances such as acetylcholine or sympathin. These *chemical mediators* initiate mechanical contraction and electrical disturbances in the muscle fibers which involve the liberation of energy by the muscle itself. The reaction of the muscle fibers is not all-or none, however, except as liberation of the mediator is dependent upon an all or none nerve impulse. Furthermore, in smooth muscle there is apparently no propagated disturbance equivalent to the electrochemical type of nerve impulse. Instead, conduction here occurs by simple diffusion of the chemical mediator from the region where it is liberated. It appears probable that similar chemical transmission also occurs in the synapses of the central nervous system (see also p. 391).

The gray matter of the brain exhibits complex electrical activity (see Chapter 18). It is not yet established to what extent this electrical activity represents all-or none reactions such as nerve impulses and to what extent it is based upon processes more nearly analogous to those in smooth muscle. It is also possible that the cortical potentials are generated in part by the chemical processes of recovery following activity. Such *after potentials* which can also be detected in the nerve fiber

following the passage of a nerve-impulse, are not strictly all-or-none in character.

THREE PRINCIPLES AIDING THE STUDY OF CELLULAR POTENTIALS

In making applications of classical electrophysiology to structures such as the inner ear, one point must be emphasized. Classical electrophysiology has studied certain cells or parts of cells, particularly skeletal muscle and the axons of neurons. These cells constitute a special case—that of long cells which can be injured at one point and still remain relatively normal and active at another point. These are cells in which activity may spread as a wave from point to point, and the periods of activity at different regions may be separated in point of time. The length of the cell makes possible large differences in activity from end to end. On the other hand, cells which are small and cells which are symmetrical are far more difficult to study electrically.

Smooth muscle, composed of cells which are small relative to the organ which they constitute, and relative to any ordinary electrodes, shows electrical changes associated with activity, but the interpretation of these changes is by no means as simple as in the skeletal muscle. In fact, in smooth muscle it seems extraordinary that we can detect systematic electrical changes. Such changes imply, in the first place, that an electrical asymmetry appears in the individual cells. If all points of the surface of a cell underwent the same change at the same time, there would be no loss of symmetry and no change in the external electrical field in the neighborhood of the cell. There must be, in this case, an asymmetry of the electrical changes in the individual cell. Furthermore, since the individual units are myriad in number, there must be some systematic orientation of these units, as in the electric organ of *Testudo*, so that the electric field which is produced by one cell is not canceled by that of another. In other words, even granting the production of an electrical disturbance by each individual cell, we must infer a

more or less systematic orientation of these cells if the disturbances are not to be statistically evened out to a dead level. These two principles of *asymmetry* and of *orientation* of the electrically active units in tissue are provided anatomically in most tissues hitherto studied. They are apparently present in others, such as the gray matter of the nervous system, smooth muscle, gland cells, and, as we shall see, the organ of Corti.

A third principle facilitating the detection in a tissue of the activity of its component cells is *synchronization*. This principle has long been appreciated in the skeletal muscle, and even more so in the nerve. The synchronized action potentials of the individual fibers, following an electrical stimulus applied to a large nerve, can be detected easily with an unaided string galvanometer, but the detection of random, asynchronous activity in the fibers of that same nerve requires the aid of amplification. Fortunately for the electrophysiology of audition, the principle of synchronization is automatically fulfilled to a large extent by the nature of sound. We shall consider in Chapter 16 how each sound wave tends to set up a synchronized volley of nerve impulses. Synchronization makes it possible to study, with comparative ease, the activity of auditory pathways buried deep in the substance of the midbrain, and the synchronization of the sensory cells of the inner ear, when they generate their tiny electric fields in response to sound waves, gives rise to a microphonic action of the cochlea as a whole.

CONDUCTION IN NERVES

The all-or none law of the nerve impulse has a profound significance for psychophysiology. All nerve impulses are fundamentally similar, although their speed, whether measured as velocity of conduction or as the rate of electrical change at a given point, varies systematically from fiber to fiber as a function of size, but the rate is constant for a given fiber. Only one kind of nerve impulse has ever been detected. It is true that the peripheral portion of a nerve fiber dies when severed from the cell body, and we may infer from this a *trophic* influence proceeding from the cell body. This must be of the nature of

the spread of chemical material, and its velocity has been measured by Parker and Paine in terms of centimeters per day. Obviously this effect can bear no relation to the problem of sensory perception.

The only other serious suggestions of conduction of non-impulsive influences along nerve fibers are contained in the observations on *electrotomic* effects described by Barron and Matthews, in the theory of "chronaxie de subordination" of Lapique, and in the "retrograde influence" of Rosenbluth and Ortiz. It is a well established fact that a difference of electric potential established along a nerve fiber gives rise to an extra polar electric gradient. The normal polarization of the axon is increased or diminished for a short distance away from the electric source. This effect is known as *electrotonus*. Barron and Matthews found that some afferent fibers in the spinal cord show intermittent failure to conduct impulses, a transient block to conduction, which is best explained as due to a purely physical spread of polarization from the electrically active gray matter of the spinal cord along collateral branches to the main axons, there producing an 'electrotomic block'.

The phenomenon of 'subordination' is apparently another manifestation of changes in polarization which induce alterations of excitability, velocity of conduction, and so on. There is still some doubt as to the validity of the fundamental observations and still more as to their interpretation, but for our immediate argument it is significant that these changes are supposed to be induced in one neuron by the activity of another, and that the effects emanate from a hypothalamic center toward the periphery. There is no suggestion that peripheral stimulation of sense-organ might alter the polarization or degree of subordination of a center except by the transmission to it of impulses, even though the theory might allow changes in sensory threshold due to central modification of the properties of an afferent nerve. The theory of subordination, important as it may become for psychophysiology if finally established upon an adequate experimental basis, must as yet be regarded with open minded skepticism.

The retrograde influence of Rosenblueth and Ortiz is postulated by a process of exclusion, in order to explain certain central effects following the cutting or blocking by local anesthesia of motor fibers in the phrenic nerve. The experiments make it difficult to avoid this assumption of a property of neurons which differs from the properties manifested in the process of conducting nerve impulses, but the effect appears only after interruption of functional activity of the peripheral axon, and its nature is entirely obscure.

We remain, therefore, with the proposition that the only rapid change which proceeds centrally along an afferent nerve fiber is the nerve impulse. This impulse is all-or none in character, and, although its intensity and time course may vary within limits as a function of fatigue, these limits are definitely established by the morphology of the fiber.

RELATION OF NERVE IMPULSES TO SENSATION

The afferent nerve from a sense-organ, such as the eye or the ear, represents a bottle neck through which all the variety and gradations of sensation of the entire sense modality must pass. The number of physiological variables in the afferent nerve are strictly limited. *There is significant freedom in the matter of (1) how many fibers and of (2) which fibers in the nerve may carry impulses, and of whether (3) one or several impulses pass up each fiber and, within limits, (4) at what frequency.* There is an upper limit to the possible frequency at about 1000 per second imposed by the recovery or refractory period of the nerve fiber. *There is no variation in the size of the impulses as a function of the intensity of the stimulus.* Such variations in size as occur during equilibration or fatigue are a function of frequency and of duration of activity, and hence the variation in size is not an independent variable. *There is also freedom in (5) the temporal relations of impulses in different fibers,* since each fiber is functionally quite independent of its neighbors.

These, then, are the physiological dimensions of sensations as they pass along the afferent nerve, and it is the task of

psychophysiology to examine the activity of the cochlea and of the auditory nerve and to compare them with the corresponding auditory sensations in order to ascribe, as far as possible, the correct physiological dimensions to each dimension of auditory sensation

The problem of the psychophysiology of sensation is partly, but not completely, solved by such an analysis in terms of nerve-impulses. The function of nerve-fibers is purely that of conduction. The message is coded, so to speak, by the sense-organ, dispatched on the nerve-fibers, delivered promptly by them at another station, and there decoded and related to other messages from other stations. Our first problem is to detect the messages in transit and learn their code. This task is relatively easy, since we believe we know all of the possible variables in the code and can tap the wires with fair efficiency. The next problem is the interpretation of activity at the synaptic centers. This is not so easy, since we do not yet know the possible variables in the function of cell-bodies and synapses. The anatomy is far more complicated when synapses are involved; a new set of physiological laws confronts us and implies a new set of physiological variables underlying them. In terms of these new variables the sensory messages are rewritten, and, when we tap the centers electrically, a new pattern of activity confronts us. The centers seem to code their messages in a new language and we are still seeking the clue to its translation.

PROPERTIES OF SYNAPSES

The differences between synaptic or central transmission and transmission in the nerve-trunk have been derived chiefly from the study of spinal reflexes. They may be summarized briefly as follows:

1. *One-way conduction in the synapse.* The activity passes from axon across synapse to dendrite or cell-body, but not in the reverse direction. In the nerve-trunk the impulse can travel equally well in either direction.
2. *Greater sensitivity of the synapse to adverse conditions.* Anesthetic drugs, fatigue, and lack of oxygen, in degrees or con-

centrations easily tolerated by the nerve trunk, stop synaptic conduction

3 *Delay in conduction through the synapse* At least 0.5 msec and sometimes as many as 2 or 3 msec are required for transmission across the microscopic synapse, whereas the velocities are from 1 to 100 meters per second along axons

4 *Summation of impulses at synapses* Although it is possible that a single impulse in an axon may activate the next neuron beyond a synaptic junction, it is usually necessary for several impulses to arrive either (a) in succession over the same axon, giving *temporal summation* or (b) nearly simultaneously over different axons, giving *spatial summation* In the axon a single impulse once started traverses the entire axon

5 *Inhibition at synaptic junctions* The arrival of impulses at certain synapses does not tend to excite the next neuron, but instead tends to suppress any activity which may be in progress and make the neuron more resistant to excitation by impulses arriving over other pathways The nearest analogy to this in the axon is the electrotonic block of impulses discussed earlier in this chapter Even this effect seems to depend upon the proximity of synaptic centers

6 *Spontaneous activity of gray matter.* Present evidence suggests that certain brain cells are normally in a state of rhythmic activity, sending a series of impulses along their axons even in absence of stimulation by afferent impulses This, like many of the properties here listed, may well reside in the cell body rather than in the synapse proper, which is the anatomical junction between two neurons, but for our purposes there is no need of distinguishing between the two The contrast lies between the conduction of impulses by peripheral axons and the new properties introduced by axon terminations, synapses, dendrites, and cell bodies in the gray matter of the central nervous system Spontaneous rhythmic discharge is not seen in the axon except for a brief period following an acute injury, or in an abnormal chemical environment

The modifications of conduction introduced by the synapses or cell bodies may well be related to the high rate of metabolism

of nerve-centers, as compared with the greater economy of the fibers, and to the probable chemical mode of transmission between neurons as opposed to the electrochemical mechanism of the impulse. At present we are still seeking to understand the nature of central action and are not yet prepared to undertake psychophysiological correlations with either chemical or electrical events occurring in the gray matter of the nervous system.

CHAPTER 13

THE MICROPHONIC ACTION OF THE COCHLEA

THE electrical activity of the cochlea has been employed as a tool in the analysis of both physical and physiological problems. The original impetus to this type of work was given by Wever and Bray (1, 2) when they reported that, after placing electrodes upon the medulla or the auditory nerve of a decerebrate cat, they were able, by listening with telephone receivers to the amplified signals, to recognize, not only pure tones used as stimuli, but even words spoken to the cat. This observation immediately attracted the attention of both physiologists and psychologists, and its verification and extension were undertaken in several laboratories.

HISTORICAL

The presence of action potentials in the eighth nerve and the brain stem was taken for granted even before it was directly demonstrated by Buytendijk in 1910. Buytendijk, in that year, with merely a string galvanometer, recorded the action-current of the auditory nerves of rabbit and guinea pig in response to a pistol shot. Seventeen years later, Forbes, Miller, and O'Connor, using a string galvanometer and one stage of amplification, detected responses from the medulla of the decerebrate cat in response to sudden sounds. Synchronization with rapidly repeated clicks was observed up to 200 per second, but the limitations of the recording device prevented analysis at higher frequencies.

Then Wever and Bray in 1930 reported the reproduction of speech in the auditory nerve. They proved that the effect was truly biological and not a mere physical artefact. In their experiment we also encounter the first detection of the microphonic action of the cochlea—a true microphonic action, dif

ferent from the action potentials of the auditory nerve. Wever and Bray did not suspect the dual nature of their electrical phenomena, however, and interpreted them exclusively in terms of action potentials. Adrian suggested a "microphonic action of the cochlea" and gave considerable experimental evidence in support of this view, but in collaboration with Bronk and Phillips he apparently reversed his judgment, and tacitly assumed the existence of only one type of response—true action potentials. Saul and Davis pointed out the distinction between the two types of response by showing that one of them (the action potential) is limited to relatively low frequencies, is easily suppressed by anesthetics, and is localized in the auditory pathways and nuclei of the medulla, whereas the other (the aural microphonic) occurs at high as well as low frequencies, is resistant to anesthesia and death, and is generated in or near the cochlea. Meanwhile Wever and Bray (4, 5) extended their studies to other animal forms. All mammals studied showed effects very similar to those shown by the original cats. Turtles reacted similarly to low frequencies, but were unresponsive to high tones, whereas insects gave only asynchronous nerve impulses (see, however, p. 399).

THE ELECTRICAL ACTIVITY OF THE COCHLEA

The *microphonic action* of the cochlea, or *cochlear response*, as it has previously been called, denotes the generation in the cochlea of electric potentials when sound waves activate the ear. These potentials reproduce the frequency and the wave form of the sound waves throughout the range of audible frequencies, and their latency with respect to the sound wave is less than 0.1 msec—perhaps much less. They are not to be confused with the action potentials of the auditory nerve, which, as we shall see, show synchronized response to only a restricted range of lower frequencies. The wave form of the action potentials may differ considerably from that of the stimulating sound, and their latency is at least 0.7 msec. Action potentials fall in the all-or-none, self-propagating category of disturbance described in Chapter 12, whereas the microphonic action of the

cochlea is apparently a distortion potential and represents the transformation of the mechanical energy of the sound wave into electricity without further contribution of energy by the tissue. It is to emphasize this distinction that we here employ Adrian's phrase "the microphonic action of the cochlea" rather than 'cochlear response' since *response* has acquired a physiological connotation suggesting the *liberation of energy* in some specific manner, as in the nerve impulse or muscular contraction. Another apt designation of this effect is *cochlear* or *aural microphonic*.

There is no doubt that the microphonic action occurs in the cochlea, although it may be detected from almost any part of the head when sufficient amplification is used. The signals are strongest, however, if the petrous bone is included between the two electrodes and best of all when one of the electrodes is placed in contact with the round window, or, in the case of the guinea pig, with the apex of the cochlea. Contact can be made to one of these points with a cotton wick moistened in salt solution, and the circuit completed through an indifferent electrode on the muscles of the back of the neck. The potential, as measured at the round window, may amount to a maximum of approximately 1 millivolt when the ear is stimulated by a loud pure tone. If the tympanic membrane is damaged, or the ossicular chain interrupted, the microphonic action is diminished, but it can still be obtained when the sound waves are carried to the cochlea by bone-conduction.

Post mortem Activity When the experimental animal is more and more deeply anesthetized, or when it dies during the experiment, the microphonic action is only slightly affected until the circulation fails. The potentials then fall to a low level. Ligation of the carotids and compression of the vertebral artery causes a similar reduction to a value of from 5 to 20 per cent of the original strength within 2 or 3 minutes. Occasionally, with failure of the circulation, the potentials almost completely disappear within a very short time. More frequently, however, they persist at a low level, continuing to fall slowly for from one to several hours. The exact moment of final extinc

tion is difficult to determine, for it depends on the degree of amplification and the strength of stimuli employed. So far as it has been investigated, this post mortem activity appears not to differ in any significant way, other than in magnitude, from the normal ante mortem activity. If the depression has been brought about by compression of arteries, the effect is reversible: the microphonic action returns upon re-admission of the circulation. These facts assure us that the piezoelectric effect in the cochlea does not depend simply upon frictional effects of endolymph moving in its channels or upon the vibration of ossicles and membranes. Cooling the cochlea by placing ice in the bulla, or on the petrous bone, causes a similar partial depression without significant change in the upper limit of frequency. This is another important point differentiating the microphonic effect of the cochlea from the action potentials of the auditory nerve.

THRESHOLD OF THE COCHLEAR MICROPHONICS

If, as appears probable, the cochlear microphonic is a true piezoelectric effect in which the potential generated is proportional to the distorting force applied to the hair cell, we should expect to find no 'threshold' for this effect in the sense that we find a threshold for the excitation of a nerve fiber. A fiber reacts in an all-or-none fashion as soon as a stimulus achieves a certain finite value—the threshold value. The cochlear microphonic, however, is a continuous function of the intensity of the stimulus. Therefore, the lowest value of the stimulus which will generate a cochlear microphonic is determined only by the ultimate quantal nature of electricity. With available techniques we cannot, of course, follow the microphonic effect to these very small values, and so we designate as 'threshold' the lowest values which we can conveniently measure.

The relation of a just-detectable microphonic effect to the energy and frequency of the stimulating sound resembles rather closely the human audibility curve, particularly when the latter is determined by the same stimulating apparatus (Fig. 123). A 'just-detectable effect' is, in practice, about 1 microvolt when

a cathode-ray oscillograph is employed as indicator, or a little less when measured with a sharply tuned circuit, such as a wave-analyzer. Such a 'threshold effect' is produced in guinea-pigs by the least sound-energy when the frequency lies between 700 and 2000 cycles. The sensitivity is less for both higher and

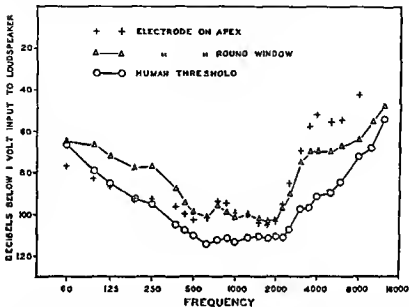


FIG 123 Average threshold-curves from 17 normal guinea pigs and 8 human ears. The threshold for the cochlear microphonic was taken as the electrical input to the loud speaker which yielded a just visible wave of about 1 microvolt on a cathode ray oscillograph. The human ears were tested by placing the speculum through which sound was delivered to the ear of the guinea pig into the observer's external meatus and requiring the observer to report the presence or absence of the tone. Only observers under 30 years of age were used. (Stevens, Davis, and Lurie.)

lower frequencies, by an amount depending on what part of the cochlea is nearest to the recording electrode. The significance of this fact will appear later. The absolute sensitivity of the animal appears to be a little less than that of the human observer, but it should be remembered that the animal's 'threshold' is here taken as an arbitrary potential, dependent upon the resolving power of an amplifier. This just-detectable effect may well be above the threshold for activation of the most sensi-

tive nerve fibers, since Kemp, Coppée, and Robinson frequently observed a threshold for action potentials in the medulla some 10 db below the round window 'threshold' which was measured simultaneously in the same animal. With this correction, the threshold functions for animals and human observers would coincide very closely indeed. In fact, the electrical audiogram of the most sensitive animal preparations is nearly superimposable on the average curve for the normal human ear. The systematic irregularities at 250 and 700 cycles in the curve for the guinea pig in Fig. 123 are almost certainly due to interference by action potentials—a fact to be considered later.

LIMITS OF FREQUENCY

At very high and at very low frequencies, more and more sound energy is required to produce a detectable microphonic effect. This makes it impossible to speak with precision about upper and lower limits of frequency. As better sound systems and better recording amplifiers have been employed, the reported upper limit of response has risen from 4100 cycles, originally mentioned by Wever and Bray, to more than 16,000 cycles. Here the limit still appears to be fundamentally instrumental, since the voltage of the microphonic is small and high sound intensities are necessary. It seems quite reasonable to assume that the microphonic persists at least as far as the upper limit of hearing.

The lower limit presents a similar problem, for the necessary intensity of sound rises progressively as the frequency is reduced. Figure 123 shows, however, that if the electric potential is measured at the apex instead of at the round window the threshold curve rises more slowly at low frequencies. Very slow waves of less than 1 per second are often seen to be correlated with the pressure changes produced by movements of the door of the experimental room, and also by contraction and relaxation of the intra-aural muscles (H. C. Wiggers). In their investigation of the effects of low tones, Wever, Bray, and Willey demonstrated cochlear microphonics in response to fre

quencies as low as 5 cycles. Ultimately, however, a limit must be reached when pressure differences between the scala vestibuli and the scala tympani are equalized through the helicotrema as fast as they are produced. Nevertheless, it is perfectly clear that the lower limit of the microphonic is far below the 20 cycles which is conventionally assigned as the lower limit of pitch perception.

WAVE FORM

The wave form of the cochlear potential corresponds fairly closely to that of the stimulating sound wave. The complex waves of human speech are reproduced accurately enough to allow listeners to recognize the speaker by the quality of his voice. Although a pure sinusoidal sound wave is reproduced under favorable circumstances as a sinusoidal electric wave, there are two major limitations to the perfection of the reproduction. In the first place, the intensity of stimulation must not be too great, else higher harmonics will distort the wave, as shown in Fig. 124. This distortion undoubtedly represents the 'subjective' or, better, *aural harmonics* which have long been familiar to psychologists and which have been considered in Chapter 7. In the second place, we often see at frequencies below 1000 cycles a notch or hump in the main wave (Fig. 124). This latter distortion can also be measured in terms of harmonics, mostly second and fourth. Its basis is not, however, a mechanical nonlinear distortion, but merely the presence of the action potential of the auditory nerve. The nerve fibers discharge more or less synchronously once during each cycle, and an electrode on the round window or apex records their action potentials simultaneously with the microphonic wave.

There is a constant latency of approximately 0.7 msec between the arrival of a sound wave at the basilar membrane and the appearance of the corresponding action potential in the nerve. Consequently, as the frequency is changed, the hump due to the action potential shifts phase relative to the microphonic wave. At frequencies near 1000 cycles the action potential may merge quite smoothly with the succeeding micro-

phonic wave and be scarcely noticeable. At higher frequencies, the action-potentials recorded from the auditory nerve become much smaller and finally asynchronous (see Chapter 17), so that the distortion of the wave due to this cause becomes negli-

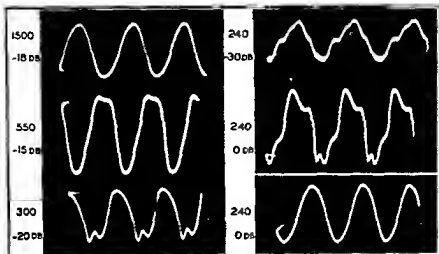


FIG 124 Standing wave oscillograms recorded from the round window of a guinea pig, and (lower right) a control oscillogram of sound waves recorded by a crystal microphone. The sweep-circuit of a cathode ray oscillograph is synchronized with the sound waves. The luminous spot then traverses the same path repeatedly and produces a standing wave pattern which is photographed

The 1500-cycle record shows a nearly sinusoidal wave-form. At 550 cycles the action potential appears as a notch at the peak of the microphonic wave. At 300 cycles and at 240 cycles the action potential stands in a different phase-relation to the microphonic. The cochlear microphonic is nearly maximal in the first four records. In the fifth (240 cycles at 0 db) the sound intensity is supramaximal and the cochlear microphonics show the strong aural harmonics which are introduced by nonlinear distortion in the middle and inner ear. The lower right hand record, taken by a crystal microphone, shows the purity of the sound wave at 0 db. (The reference level, 0 db, is approximately 115 db above human threshold at 1000 cycles.)

ble. It is plain, then, that the admixture of action-potential interferes with exact measurement of the cochlear microphonics at certain frequencies, but, with this limitation, it seems safe to conclude that the cochlear microphonic reflects with great accuracy the time-course and wave-form of the mechanical disturbance within the cochlea.

POLARITY AND PHASE RELATIONS

The polarity of the microphonic wave depends upon the location of the exploring electrodes. If we record the potential between the round window, which is electrically continuous with the scala tympani, and an indifferent electrode on the neck, we find that the development of positive external pressure on the tympanic membrane causes the round window to become electrically negative (cf Fig 133, p 342). Negative pressure causes it to become electrically positive. It is of some theoretical importance that the initial electrical change may be either positive or negative from the resting potential, and is not restricted to a single polarity, as in the case of the nerve impulses.

As the round window becomes negative, the oval window and stapes, electrically continuous with the scala vestibuli and scala media, become electrically positive, and, in the guinea pig, the apex of the cochlea, which is easily accessible and is separated from the scala vestibuli and scala media by only a thin shell of bone, also becomes more positive. The opposite sign of the electric potential at apex and at round window implies that the two sides of the basilar membrane develop opposite electric charges in response to mechanical pressure on the tympanic membrane.

Efforts to determine more accurately the phase relation between the potentials at round window and apex showed that it shifted somewhat as a function of frequency (Stevens and Davis). At 60 cycles the two potentials were almost 180° out of phase, but the difference approached 90° as the frequency was increased to 4000 cycles. The individual measurements varied considerably, however, under the method used. The interpretation of these phase-differences is uncertain, particularly when the differences are other than 180° . The presence of a complex electric impedance of the sort embodied in all living tissue (Stevens and Davis) may contribute to them, or they may also be an expression of actual differences of phase in the mechanical events toward the two ends of the basilar membrane (cf Fig 118, p 285).

RELATION TO SOUND INTENSITY

The voltage of the cochlear potential increases as a continuous function of the intensity of the stimulating sound. No evidence has appeared to indicate any step-like additions of all or none units, as in neuromuscular activity. At low intensities, provided disturbing factors are eliminated, the potential is

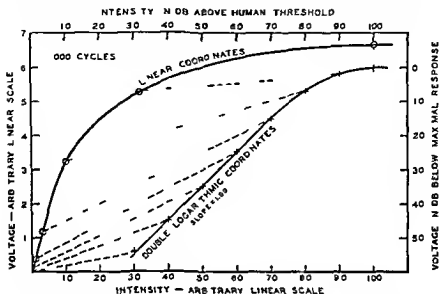


FIG. 125 The voltage of the cochlear microphones is plotted as a function of intensity in linear and also in double logarithmic coordinates. The units of the linear scales are arbitrary. Corresponding points on the two curves are connected by broken lines to show what a small part of the upper curve is represented by the long straight portion of the lower curve. These microphones were obtained from the round window of a guinea pig and measured with a sharply tuned wave-analyzer. (Data from Newman, Stevens and Davis.)

directly proportional to the amplitude of the stimulus. At higher intensities the curve becomes concave toward the intensity axis, as shown by the upper curve of Fig. 125. The cochlear potential later passes through a maximum, and, at very high intensities, declines markedly. The deviation from the linear relationship usually occurs when the cochlear potential has reached about 20 per cent of its ultimate maximum. When the voltage of the cochlear microphone is plotted against the logarithm of the sound intensity (decibel scale), the function

appears as a sigmoid curve, as in Fig. 129. The data may also be plotted as the logarithm of the microphonic against the logarithm of the sound-intensity. The linear relationship at low intensities then appears as a straight line with a slope of 1.0, as shown by the lower curve in Fig. 125. This form of

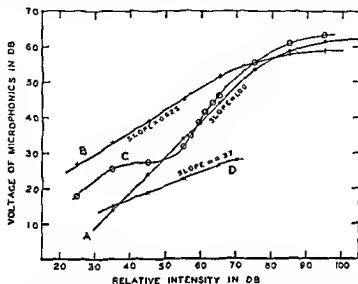


FIG. 126 Variations in the relation between voltage of the cochlear microphonic and sound intensity. Double logarithmic coordinates.

A—from the apex of a guinea pig's cochlea. Frequency 1500 cycles. This slope of 1.00 at low intensities is the ideal case.

B—from the apex of a guinea pig's cochlea. Frequency 1500 cycles.

C—from the round window of a guinea pig. Frequency 1000 cycles. Irregular curve due to interference by action potentials.

The data for curves A, B, and C were obtained by means of a sharply tuned wave-analyzer (Stevens and Davis, unpublished).

D—from the round window of a pigeon. Frequency 5000 cycles. (Data from Wever and Bray, 8.)

Curves A, B, and C are shown in the correct relation to one another with respect to intensity and to voltage. Curve D is placed arbitrarily in what is judged to be its proper relation to the other three curves.

representation has been widely used, but it should be noted that, owing to its logarithmic character, it exaggerates the importance of the small potentials at low intensities. It is for just these small potentials that measurements are most uncertain.

The slope of the straight portion of the curve in the double

logarithmic plot seems to approach 10 as a limiting value. Deviations occur (Fig 126) in the direction of a lesser slope, as low as 0.625 in the guinea pig (Stevens and Davis, unpublished) and as low as 0.35 in the pigeon (Wever and Bray 8). More rarely the slope is significantly greater than unity. The

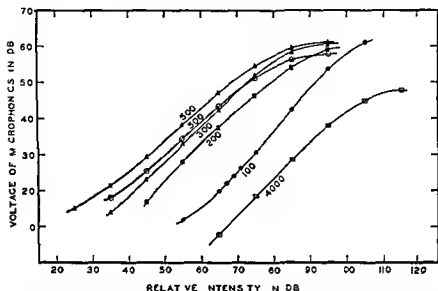


FIG 127 Typical family of voltage-intensity curves obtained at various frequencies (parameters) from the round window of a guinea pig. The voltages were measured with a sharply tuned wave analyzer. Most of the curves show slopes of less than 100 and many of them are slightly sigmoid. Curve C in Fig 126 belongs to this same family. (Stevens and Davis unpublished.)

slope of unity appears to represent the ideal case. The straightness of the line is also a limiting or ideal case. Very often there is a systematic deviation in the direction of a long flat sigmoid, as shown in Fig 127. Sometimes deviations are abrupt, significant, and reproducible, as illustrated by curve C in Fig 126. Such abrupt deviations are almost always associated with a distorted wave form, revealed by the cathode ray oscillograph. The distortions in question appear at low intensities, far below the level at which mechanical nonlinear distortion might reasonably occur, and several tests prove that they are due to the presence of an action potential component. No ready means

has yet been devised for eliminating these action potentials, although partial asphyxia and cooling may reduce them considerably. The action potentials are not sinusoidal, and, depending on their phase relation to the cochlear potential proper, they may add to or subtract from the latter. This is true whether we measure peak voltage on the cathode ray oscillograph or the root mean square alternating voltage of the fundamental frequency, with a tuned frequency analyzer or filter system. The action potentials also introduce even harmonics which may be measured by an appropriate analyzer.

We shall see (Chapter 16) that the law of increase of the action potential may be approximately, but not exactly, the same as that of the cochlear potential. Addition of nerve potential to cochlear potential, therefore, should, and apparently does, introduce more or less systematic deviations from any simple law.

Another physiological factor may mask the simple relation of cochlear microphonic to sound intensity. The muscles of the middle ear contract reflexly in response to sounds, and the louder the sound the stronger the contraction (Lorente de No, 1). Now, increased tension of these intra-aural muscles reduces the transmission of sounds. The reduction is very significant for low tones, but absent for frequencies above 2000 cycles (see Fig. 110, p. 267). For low tones, therefore, there is a reduction of the cochlear microphonics which is a function of the intensity of the stimulus. This fact tends to make the microphonic curve concave toward the axis of intensity. The reflex in question is depressed by deep anesthesia (Hallpike, 2) and in consequence has, apparently, escaped the attention of several investigators, but it must be considered in any study of the unanesthetized animal or normal human being.

RELATION OF MAXIMAL COCHLEAR POTENTIAL TO FREQUENCY

At low intensities of stimulation the magnitude of the cochlear potential increases in linear relation to the intensity of the stimulus. This does not continue indefinitely, for with

stronger stimuli the voltage of the cochlear microphonic increases more and more slowly and ultimately passes through a maximum. When the intensity of the stimulus is plotted on a logarithmic (decibel) scale, this maximum is rather sharp (Fig. 129). Plotted on an arithmetical scale, however, it appears as a long plateau (Fig. 125).

The intensity at which the maximal potential is developed can be determined for each frequency. This intensity does not vary greatly as a function of frequency and is some 90 db above the threshold of the microphonic at 1000 cycles. The sound-intensity which produces maximal potential is of the

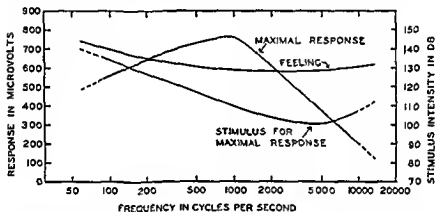


FIG. 128 The maximal voltage obtained from the round window of the cat (average of 12 cats) is plotted, as a function of frequency, against a linear scale. The sound intensity necessary to attain maximal voltage is plotted in decibels (after Covell and Black). The threshold of feeling in man is also plotted in decibels for comparison (Wegel, 2).

same order of magnitude as, although slightly lower than, the intensity at the threshold of feeling in human ears (see Fig. 128).

The maximal voltage obtainable from the cochlea is a function of the frequency of stimulation. Less voltage is obtainable at high frequencies than at low frequencies, but the exact form of this relationship varies with the position of the recording electrode. If the active electrode is placed in contact with the round window, the greatest voltage can be obtained at about 800 cycles in the guinea-pig. Above this optimal frequency, the maximal voltage falls off in almost linear relation to the

logarithm of the frequency, as shown in Fig 128, until at 10,000 cycles the voltage is not more than 20 per cent of the voltage at 1000 cycles (Covell and Black.) In some experiments the voltage falls off much more rapidly than is indicated in Fig 128. At low frequencies the maximal potential also falls off with frequency, but much more slowly. The maximal voltage usually obtained at the optimal frequency of 800 or 1000 cycles is approximately 1 millivolt, although Bast and Eyster report a maximum as high as 2.5 millivolts.

When the active electrode is placed upon the apex, the same type of relation is found, but the optimal frequency is considerably lower than at the round window. In fact, in some guinea pigs the optimal frequency is at 100 cycles or even less. In any case, this maximal cochlear potential is very nearly the same over a wide range of frequencies below 300 cycles. Above 300 cycles the microphonic at the apex falls off even more steeply than it does at the round window.

The measurements of maximal cochlear potential at low frequencies are less precise and reproducible than those at high frequencies because of the distortions of wave form illustrated in Fig 124. The distortion, which is particularly evident with low tones, is due to the appearance of higher harmonics in the microphonic wave and the admixture of large components originating as action potentials in the auditory nerve. In spite of the uncertainties of measurement which these factors introduce, it is quite clear that the optimal frequency at the apex is lower than that at the round window and that the maximal potential which can be obtained at the optimal frequency at the apex is greater than that obtainable at the round window.

The fall of maximal potential with increasing frequency may be due to two possible factors. It may simply be that the potential generated by the basal end of the organ of Corti is actually smaller. Or it may be that the potential across the hair cells is as large at high as at low frequencies, but that the potential does not readily make itself felt at the electrodes. This inefficiency is presumably due to an increase of electrical shunting by the tissues of the ear and head for alternating

currents of higher and higher frequency. Direct measurements have shown that the electrical impedance of tissues falls with an increase of frequency (Stevens and Davis), and the shunting action on the hair-cells may be expected to increase accordingly. The importance of this and other possible factors cannot be estimated from available data.

It should be noted here that the values for the maximal voltage obtainable from the cochlea discussed above were obtained with one electrode on the round window or the apex and the other elsewhere on the body of the animal. When one electrode is on the round window of a guinea pig and the other is placed on the apex instead of on the body, the maximal voltage may be either increased or decreased, depending on the frequency of the stimulus (Stevens and Davis).

OVERLOAD HYSTERESIS AND FATIGUE

It is evident from Chapter 8 that the ear, regarded as a mechanical system, is at first linear in relation to the intensity of the activating tone, and becomes nonlinear when about 20 per cent of the ultimate maximum of mechanical and electric response is reached. In a technical sense, this deviation from a linear relation represents an 'overload' of the system. From the physiological point of view, however, overload is not reached until the cochlear potential passes through its maximum. We have already pointed out that, when the intensity of stimulation is increased beyond the point at which maximal voltage is reached, the electric output will begin to fall off again. The diminution is a function of the intensity of the stimulation and also of the length of time which it continues. With submaximal stimulation there is no suggestion of fatigue—that is to say, no diminution of activity from prolonged stimulation. Stimulation which is 40 db supramaximal, however, may reduce the cochlear potential to 30 or 40 per cent of its original maximal value. When, after such depression, the intensity of stimulation is diminished step by step and the corresponding cochlear potentials are measured, the original curve is not retraced (see Fig 129). The points follow a new and somewhat lower curve

The threshold is also found to be somewhat elevated, and a period of recovery is necessary before the original threshold and the original voltages for a given intensity can be obtained again. The period of time necessary for recovery from such an overload depends upon the severity of the depression. If the depression is slight, a few minutes' recovery may suffice;

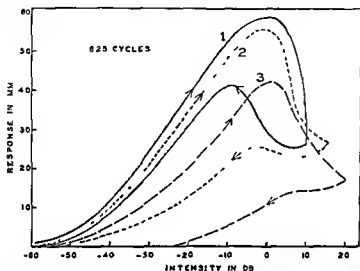


FIG 129. The size of the cochlear potential as a function of the intensity of the stimulus. The abscissa represents an arbitrary intensity scale against which is plotted the size of the cochlear potential as it appears on the oscillograph. The arrows indicate the direction of intensity variation for the three different hysteresis loops. The intensity was changed by 10 db at 20-second intervals, and curves 1, 2, and 3 were traced in that order. As the response went through the maximum, the wave form became highly complex (Stevens and Davis)

but, if it is severe, it may be a matter of hours before the original sensitivity is restored. To this phenomenon we may apply the descriptive term *hysteresis*, because it emphasizes an analogy to physical processes, such as the magnetization and demagnetization of iron. The hair-cells and iron are similar in that they must both be restored to their original state before a previous response-curve can be retraced. The curves of Fig. 129 may aptly be compared to hysteresis loops.

The depression following supramaximal stimulation was de-

scribed by Hughson and Witting and was termed by them *auditory fatigue*. If by 'fatigue' we mean all depression of response as a result of previous activity, the term is obviously appropriate, but it seems that the process is more akin to a temporary pathological damage of the responding mechanism, since it may require hours or days for recovery. It should be observed that this effect does not appear except at intensities considerably beyond the intensity required to obtain maximal voltage from the ear. We may therefore refer more aptly to the phenomenon as *overload*.

The disruptive effects of still more violent stimulation, and the degenerative changes induced by long continued stimulation, will be described in Chapter 15, and the fact that such strong stimulation causes temporary or permanent damage to the hair-cells makes it reasonable to attribute the overload and hysteresis effects also to the hair-cells. This is in accord with the view that the hair-cells are the structures which generate the microphonic potentials of the cochlea (Chapter 14).

IMPULSIVE STIMULI

Our description of the microphonic action of the cochlea has so far been based upon stimulation by pure tones, which are either steady or at least alter gradually, as in the modulations of the human voice. The proposition that the cochlear microphonics reproduce accurately the pattern of the sound waves impinging on the ear must be qualified when the stimulus is a very brief train of waves, such as the tick of a watch, and also when we consider the abrupt onset and cessation of pure tones.

Impulsive stimuli in the form of sharp 'clicks' may be conveniently generated by discharging a condenser through a loud speaker. The quality of the click may be altered by the physical characteristics of the loud speaker employed. Condenser microphone and cathode ray oscillograph show that, depending on the type of loud speaker employed, the physical disturbance, in terms of sound waves, is a train of waves whose frequency is from 2000 to 15 000 cycles or more, beginning abruptly but falling off very rapidly in intensity (Fig. 130 B). The cochlear

microphonic, and the succeeding action potential, which is generated by such a click is shown in Fig 130 *A*. It is a series of one to three or four waves, each 0.5 to 0.7 msec in duration, which rapidly decline in amplitude. The pattern corresponds quite closely to the pattern of vibration of the ossicles in response to the sharp sound generated by an electric spark (Fig 109, p 263)

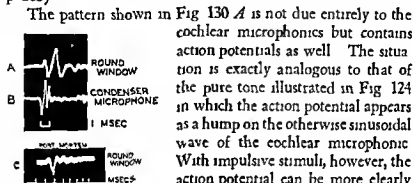


FIG 130 Oscillograms of the cochlear microphonics in response to clicks

A From the round window of a cat in response to a dull click. The pattern is a composite of microphonic and action potential.

B Sound wave pattern of the click recorded through a condenser microphone.

C Post mortem cochlear microphone from the round window. The stimulus is the same as for *A* except that its intensity is greater. The action potential component has disappeared (Davis, Derbyshire, and Saul).

microphonics and shows in the electrical record the natural period of the ear as a whole.

The details of wave length, wave form, abruptness of onset, etc., of the electrical pattern depend upon the pattern of the train of impinging sound waves. These minor differences are

The pattern shown in Fig 130 *A* is not due entirely to the cochlear microphonics but contains action potentials as well. The situation is exactly analogous to that of the pure tone illustrated in Fig 124 in which the action potential appears as a hump on the otherwise sinusoidal wave of the cochlear microphonic. With impulsive stimuli, however, the action potential can be more clearly differentiated, as we shall see in more detail in Chapter 16 (cf particularly Fig 147). The action potentials do not appear until at least 0.6 msec after the first wave of the cochlear microphonics. The first cycle of the pattern in Fig 130 *A* is exclusively cochlear microphonics and can legitimately be compared with the pattern of mechanical vibration shown in Fig 109 (p 263). The later waves of Fig 130 *A* are a complex mixture of microphonic and action potential. Fig 130 *C*, taken after the death of the animal, represents pure cochlear

reflected, in turn, in the pattern of nerve-impulses which they generate. This corresponds to the obvious psychological fact that we can detect differences in the tonal quality of the clicks produced by different instruments.

On-Effect. The record of the cochlear microphonic generated by the sudden onset of a strong pure tone is complicated (Fig. 131 *B*). Even when we arrange to start the stimulus



FIG 131 Oscillogram showing the on-effect and off-effect in the cochlear microphonic.

A Sound waves at 2500 cycles recorded by condenser microphone. The on-effect and off-effect of the loud speaker are just visible as a small transient wave at the beginning and another at the end of the main wave-train. The slight temporary reduction in amplitude near the beginning of the wave train is due to interference by an echo in the sound tube.

B Cochlear microphonics from the round window of a cat in response to the same sound waves at 2500 cycles. The on-effect and off-effect introduced by the ear are very prominent. The response to the tone is nearly maximal. The on-effect and off-effect are less prominent with less intense tones. Note the similarity of the on-effect and off-effect to the response to a click shown in Fig. 130A. (Derbyshire and Davis, 2)

without a gross physical transient, to avoid the production of echoes, and to anesthetize the animal so deeply that the muscles of the middle ear give no reflex contraction—even with all these precautions, the onset of electrical activity is not smooth and simple. A pattern very closely resembling that resulting from a single isolated click initiates the activity. When the stimulating tone is very strong, the on-effect may be several milliseconds in duration. The size and exact pattern of the on-effect depend somewhat on the phase of starting the tone, that is to say,

whether the electric current to the loud speaker is closed when the electric wave is near peak voltage or near zero voltage. During the on-effect, however, the response to the individual waves of the stimulating tone appears. The frequency and wave form of the stimulating tone are reproduced within 1 or 2 vibrations, although they are superimposed on the on effect. There is no long-continued build up of response, such as would be expected if the ear were a sharply tuned, slightly damped resonating system. It is also evident that any sudden disturbance, whether an isolated click or the beginning of a continuous tone, causes a disturbance whose form depends upon the characteristics of the ear as well as those of physical stimulus.

Off Effect When a stimulating tone stops abruptly, electrical activity does not immediately cease. Instead, it subsides gradually, according to a pattern very much like that of the on effect. For a given intensity of stimulation, the off-effect is usually less prominent than the on effect, but both consist of rather similar waves of about the same frequency which decline with about the same rapidity. Figure 131 *A* shows that both on-effect and off-effect are observed experimentally under conditions in which records taken through a condenser microphone apparently show no corresponding disturbance in the physical stimulus. If a listener's ear is placed in the position of the condenser microphone, however, the listener reports that the tone seems to begin and to end with a distinct click. The click in this case is primarily an aural click, generated by the mechanism of the ear.

The 'click pattern,' the on effect, and the off effect all apparently express the same fundamental fact—namely, that the ear is essentially a mechanism possessing inertia and elasticity. The period of vibration disclosed by these transient patterns corresponds fairly well, as we might expect, to the range of frequencies to which the ear is most sensitive. In the experiments with cat and guinea pig it will be recalled that these frequencies lie between 750 and 2000 cycles. It has been pointed out in Chapter 10 that the transmission system of the ear is considerably, but not completely, damped. This is true for the general over

all vibration revealed by the 'click response' and the on effect and by the mechanical vibration of the ossicles. The cochlear microphonics furnish no evidence of undamped resonant structures, except for this natural period of the transmitting system as a whole.

It is not surprising that the cochlear microphonics for click, on effect, and off-effect should resemble one another. When we analyze a brief auditory stimulus, we find that the sudden beginning and the sudden termination of a tone are equivalent to the appearance of acoustic energy over a wide range of the spectrum (cf p 103). A nearly instantaneous change of pressure, representing a click or a tone that is started or stopped, is represented by a nearly continuous band of frequency components. In a certain physical sense, then, a click is actually generated by the sudden starting or stopping of a tone, and it is not surprising that the corresponding cochlear microphonics resemble one another. In interpreting the on-effect, it is helpful to recall that a wide spectrum, similar to that represented in Fig 39 (p 104), is present. At the onset the ear starts to respond to all the components, including the principal frequency. All except the principal tone are quickly damped out, however, so that the on-effect is transient, but the response to the principal frequency persists and is revealed by the cochlear microphonic.

The response of the ear to a complex acoustic spectrum is determined in part by its own selective sensitivity. The ear is most sensitive to 2000 cycles and responds preferentially to the components of the click near its own peak of sensitivity.

COCHLEAR MICROPHONICS IN RELATION TO TRAVELING WAVES ON THE BASILAR MEMBRANE

The aural microphonics recorded electrically from the round window in response to a click present certain features which at first glance seem at variance with the concept of a traveling wave developed in Chapter 10. In the first place, the latency of the aural microphonic with respect to the time of arrival of the sound wave at the eardrum is not greater than 0.1 msec.

This brief latency seems to imply that there is no time for the propagation of a traveling wave. Furthermore, the pattern of the aural microphonic corresponds very closely to the pattern of mechanical movement executed by the eardrum and the stapes. The difficulties disappear, however, when we remember that the aural microphonic which we record from the round window is generated primarily by the movement of the portion of the basilar membrane near the round window. According to Bekesy's model, the movements of this portion should occur practically simultaneously with the inward or outward movement of the stapes and should accurately reflect the temporal pattern of this movement.

Following upon the movement of the basilar membrane near the round window, a wave of disturbance presumably travels toward the apex of the cochlea and arrives at the helicotrema after from 15 to 20 msec. Depending upon the sharpness of the sound wave of the click, the traveling wave dies out more or less rapidly as it progresses along the membrane (cf Fig 117, p 283). Hence, as viewed at the round window, the part of the cochlear potential contributed by the wave when it approaches the helicotrema becomes smaller, not only because the disturbance is getting farther away from the electrode at the round window but also because the wave itself is dying out. Added to these two factors, there is another effect which prevents clear registration of the microphonic of a click. The latency of the response of the auditory nerve is such that the first action potentials make their appearance just as the traveling wave is approaching the helicotrema. The presence of the action potentials makes it impracticable to derive from the form of the total pattern a clear picture of the late phases of the behavior of the basilar membrane in response to clicks (cf Fig 130).

CHAPTER 14

CONSIDERATIONS AS TO THE NATURE AND ORIGIN OF AURAL MICROPHONICS

THE AURAL microphonics—the electric potentials generated in the cochlea as a result of stimulation by sound—have proved of great value in the study of the function of the inner ear, but their exact nature and significance are still not entirely certain. It is generally agreed that they are generated within the cochlea. They are not generated by the tympanic membrane or by the ossicles, since these structures may be damaged, or the continuity of the ossicular chain may be interrupted at the incudostapedial joint, and yet the electric potentials will still be generated in response to sounds delivered to the cochlea by bone-conduction. In such experiments the threshold for bone-conduction is scarcely elevated (cf p 295).

The most generally accepted hypothesis ascribes the origin of aural microphonics to the organ of Corti—specifically to the hair-cells of that organ. This view is based primarily on the correlation between the apparent state of these cells and the threshold or the maximal amplitude of the microphonics. Some investigators have failed, however, to confirm this correlation and have advanced other hypotheses as to the origin of the electric potentials. One of the alternative hypotheses ascribes the potentials to the terminations of the fibers of the cochlear nerve. Another emphasizes the mechanical vibration of polarized membranes, particularly Reissner's membrane. Yet another ascribes the electrical effect to "streaming potentials" generated by the movement of fluid in the channels of the inner ear or through the pores of the various membranes. We may say at once that the neural hypothesis has been abandoned by its proponents as untenable in the light of recent evidence. The microphonics differ from the action potentials of the nerve in several fundamental respects, including differences in wave-

form, in latency, in polarity, in limits of frequency, in resistance to cold, to lack of blood supply, and to fatigue, and in the phenomenon of masking. The non neural theories share one basic feature in common: the energy of the electrical disturbance is derived ultimately from the sound waves and not from the metabolic activities of the tissues. The cochlea does not release stored energy, as does a muscle fiber or nerve-cell, but acts merely as an electromechanical transducer, converting mechanical into electrical energy. The various non neural theories differ as to which structures and which physical principles are responsible for this transformation.

A feature shared by all theories is that the structure responsible for the electrical phenomena is differentiated with respect to the upper and lower ends of the cochlea in such a way that the electric potentials generated by low tones arise near the apical end of the cochlea, and those generated by high tones arise near the basal end. The experimental evidence which demonstrates this fact will be presented in the following chapter in connection with the localization of frequency reception on the basilar membrane.

It is difficult to deny that electric potentials may be generated by movement of fluid within the cochlear canals and through the various membranes (provided such movement through the membranes actually occurs). Also, if Reissner's membrane and the basilar membrane are electrically polarized, as may well be the case, their vibration must cause some corresponding electrical disturbance (Hallpike and Rawdon-Smith 2, 3, 4). The question is whether these effects account for all or even for a significant part of the observed potentials. The hair cell theory asserts that they do not and that integrity of the hair cells of the organ of Corti is essential for the generation of the aural microphonics.

EVIDENCE FOR AND AGAINST THE HAIR CELL THEORY

1 *Congenitally Deficient Animals* Nature occasionally provides animals which lack the organ of Corti wholly or in

part Examples of such animals are albinotic cats, with white coats and blue eyes, and waltzing guinea pigs Howe and Guild examined three albinotic cats which were clinically deaf, but they could detect no electric activity in the cochleas Histologically the ears showed practically complete absence of the organ of Corti, including all its hair-cells, and also pathological changes in the macula of the saccule and collapse of the cochlear duct Davis, Derbyshire, Lurie, and Saul reported a similar case in which one ear had no organ of Corti and was inactive electrically, whereas the other ear was normal in both respects They also found that the microphonic effect was absent in a waltzing guinea pig whose organ of Corti was normal as far as the tunnel and the supporting cells were concerned, but whose hair-cells were abnormal, particularly in the basal turns An other such animal (Lurie, Davis, and Derbyshire) yielded small microphonics, with high thresholds, to tones below 1800 cycles In this animal the degenerative changes in the hair-cells were most marked in the three basal turns Another animal (Lurie, 1) showed degenerative changes in the external hair-cells throughout the organ of Corti, while the internal hair-cells were normal This animal showed an elevation in the threshold for the microphonics of 20 to 30 db throughout the auditory range Lurie and Davis (unpublished) studied two albinotic dogs and eight waltzing guinea pigs in which the microphonics and the hair-cells were both absent In some of these animals there were other abnormalities, such as collapse of Reissner's membrane or of the tectorial membrane In some animals the organ of Corti was completely absent, as illustrated in Fig 132 In others a rudimentary organ of Corti, composed of supporting cells and occasional rods of Corti but without hair-cells, occupied part of the basilar membrane In none of the animals could microphonics be detected, but in all the animals in which any normal hair-cells were present corresponding cochlear potentials were found

Bast and Eyster, on the other hand, reported studies of several animals which gave essentially normal electric potentials although the organ of Corti was either entirely absent or highly

atrophic, except for part of the basal turn. Their measurements are given in terms of microvolts of electric potential developed in response to sounds of various frequencies, generated by alternating currents of fixed voltage. These measurements are not directly comparable either with determinations of threshold, with equal potential contours, or with curves expressing maximal potential as a function of frequency. Nevertheless, the "practically normal" curve which they obtained by this method from the animal which had a normal organ of Corti in part of the basal turn is comprehensible, for, with strong stimulation, considerable electric potential may be generated by a small

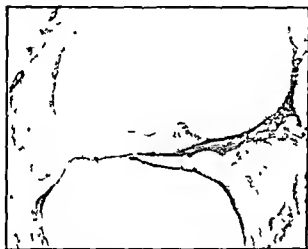


FIG. 132 Section through the basal turn of the cochlea of a waltzing guinea pig. This animal was clinically deaf and yielded no cochlear microphonics. Note the absence of the organ of Corti and the presence of basilar membrane, Reissner's membrane, and tectorial membrane. The spiral ganglion of Corti contains only a small fraction of the usual number of nerve cells. Compare this figure with Figs. 113 and 135 (Lurie, 1, 2).

portion of the cochlea. This is the general experience of many investigators. In unresponsive animals, Bast and Eyster found that Reissner's membrane was usually collapsed and adherent to the basilar membrane and organ of Corti. The hair-cells are invariably more or less abnormal in such circumstances. Also, the collapse of Reissner's membrane almost certainly modi-

fies the mechanical vibration of the finer structures of the organ of Corti beneath it, so that it is not surprising, according to either theory, that the electrical activity should be diminished. None of these considerations, however, explain the normal aural microphonics reported for an animal with no organ of Corti whatever.

2 *Stimulation Deafness* Animals exposed to strong tonal stimulation over long periods of time often show a definite depression of sensitivity which is confined to a portion of the auditory scale (cf Chapter 15). Elevation of the threshold for tones of medium pitch correlates with abnormality of the organ of Corti, particularly of the external hair-cells, over a limited range in the middle of the basilar membrane. No other anatomical abnormality is to be detected in most animals thus exposed and tested.

3 *Injection of Drugs* Chemicals, such as sodium-chloride crystals or cocaine, when placed on the round window membrane, reduce the aural microphonics. In some experiments, solutions of drugs have been injected through the round window membrane, and a typical result is elevation of threshold and depression of cochlear microphonics for high frequencies of stimulation. Histological examination, as a rule, shows damage to the sensory cells in the basal turns. We find, here again, the double correlation of elevation of threshold associated with abnormality of the sensory cells, with this elevation of threshold confined to that part of the frequency scale which corresponds to the position of the anatomical damage on the basilar membrane. The deficiency of response to high tones is associated with damage to the hair-cells of the organ of Corti in the basal turns.

4 *Surgical Damage to the Cochlea* Surgical lesions of varying degrees of severity have been produced in cats and guinea pigs by many investigators, and the effect on electrical activity determined immediately or following a period of recovery and repair. The results vary widely and various interpretations have been placed upon them. Obviously, many factors, mechanical, biological, and electrical, are involved. Some lesions

clearly interfere with the physical transmission of sound waves. These lesions include extensive hemorrhage into or collapse of the scala tympani or scala vestibuli in the basal turn, and also extensive perforation of the basilar membrane in this region. The latter lesion apparently acts as a 'short circuit' for the sound waves. Other lesions may modify the conditions of electric current flow in and around the cochlea. Either the cochlear potential may be locally short-circuited, as by an extensive lesion in the basilar membrane, or the flow of current to an external electrode may be hindered, as by thickening and scarring of the round window membrane. Depression of electrical activity from either of these general causes must be discounted in drawing conclusions as to the origin of the potentials. Many experiments are inconclusive because of such complications.

Acute surgical damage to the cochlea of the guinea pig shows that extensive lesions, such as complete removal of the two apical turns, or the opening of either the scala tympani or the scala vestibuli in such a way as to allow the cochlear fluid to ooze from the opening, does not necessarily abolish electrical activity. The threshold may be altered somewhat and the maximal response may be depressed, perhaps more for some frequencies than for others, but a surprising degree of activity often persists. A small section of normal organ of Corti may generate, at appropriate frequencies, an electric potential quite as great as an entire cochlea. It will also generate some potential at all frequencies. These facts have an obvious bearing on the question of the 'tuning' of various parts of the cochlea for particular frequencies, for they show that such 'tuning' is not sharp or circumscribed, and they make more difficult any correlation with damage to one or another structure or region within the cochlea. Nevertheless, it is possible to observe elevations of the threshold for cochlear microphonics over certain frequency ranges and to compare the limits of normal threshold with the anatomical limits of the normal organ of Corti. The consistent correspondence between definite frequencies and position on the basilar membrane (see Chapter 15) found by

this method constitutes important evidence in support of the hair cell theory

5 Degeneration of the Auditory Nerve When the fibers of the auditory nerve are cut at the internal auditory meatus, the cells of the spiral ganglion and the peripheral portions of the nerve fibers within the cochlea degenerate (Crowe). This is an exception to the usual law of Wallerian degeneration, according to which only the portions of the neurons which have been separated from their cell bodies should degenerate. Actually the ganglion cells, and ultimately the sensory hair cells as well, degenerate quite completely. The degeneration of the hair-cells may depend upon partial interference with the blood supply of the cochlea (Guttman and Barrera), which is difficult to avoid since the internal auditory artery runs in close association with the nerve (see Fig. 112, p. 270). If the artery is completely severed, the entire organ of Corti, as well as the nerve, degenerate rapidly, and following such complete degeneration no cochlear microphonics or action potentials can be detected. In most instances in which the nerve has degenerated, but in which the organ of Corti still remains normal, the microphonics persist. One such animal however, yielded no microphonics (Hallpike and Rawdon Smith, 3). The auditory nerve had been cut for twelve weeks, and degeneration, or some other type of atrophic change, may have begun, but if so it escaped histological detection. Hallpike and Rawdon Smith originally interpreted this case as evidence for a neural origin of the aural microphonics but have subsequently (Ashcroft, Hallpike, and Rawdon-Smith) abandoned this view in favor of a polarized membrane theory. One possible anatomical lesion which causes loss of the cochlear microphonics they believe to be blockage of the cochlear aqueduct. This blockage is assumed to lead to changes in the chemical relation between perilymph and endolymph, with consequent loss of a postulated polarization of Reissner's membrane.

A subsequent series of eleven cats studied by these same investigators provided the experimental basis for their present theory. The auditory nerves had been cut at various intervals

of 2 days to 23 weeks, prior to the electrical test. Some aural microphonics were found in all eleven animals. Subsequent microscopic examination revealed nearly all possible relationships between the degree of normality of the organ of Corti and the maximal cochlear potential measured at four frequencies (256, 512, 1024, 2048 cycles). Depressed microphonics were found in the presence of practically normal organs of Corti and normal microphonics with severely degenerated hair-cells. Some of these cases conform to the hair-cell theory. Others can be reasonably explained if we realize that a small region of normal organ of Corti near the round window can yield a maximal potential, as measured by an electrode on the round window, which is nearly as great as that obtained from an entire organ of Corti. All examples of this group had "normal" organ of Corti in the basal coil, and the depression of electrical activity was nearly proportional to the time elapsed since cutting the nerve. Three animals more nearly resembled the original case discussed above, in that they had normal organs of Corti but greatly reduced microphonics. Two were tested 13 weeks after operation, and it is significant that no animal showed good responses after so long an interval. In the third animal, tested after 4 weeks, the weakness of the cochlear microphonics may be related to the "considerable hemorrhage" found in the apical portion of the scala vestibuli. But, even if no explanation for this case is to be found, it requires more than one such case to render untenable the hair-cell theory, which accounts so completely for the losses of cochlear microphonics which are restricted to certain frequency limits. It is difficult to imagine why a *local* loss of polarization of Reissner's membrane should occur. The very fact that there is any localization of the electrical effects along the cochlea, as a function of frequency, strongly suggests the basilar membrane or structures attached to it as the origin of the electric potentials, and, if we admit that the basilar membrane is nearly critically damped (cf. p. 286), we avoid the chief reason given by Hallpike, Hartridge, and Rawdon Smith for turning to Reissner's membrane for the source of the cochlear microphonics.

We have attempted in some detail to offer possible explanations for this series of observations which superficially seem to render the hair-cell theory inadequate. The chief *ad hoc* assumption invoked is that denervation of the hair-cells or partial interference with their blood supply may, after 8 or 10 weeks, impair their electrical properties without necessarily causing notable microscopic alterations.

More experimental work is necessary for a final evaluation of the various theories, and much may be hoped from electrical tests in which complete response-curves, as functions of intensity at various frequencies, are obtained. These complete functions should be far more illuminating than curves for constant stimulus, for maximal response, or for threshold alone. In the meantime it appears that the hair-cell theory has the advantage of describing adequately a greater number of the known facts than do the alternative suggestions.

THE HAIR CELL THEORY OF THE AURAL MICROPHONICS

The hair cell theory assumes that all, or nearly all, the microphonic effects of the cochlea depend upon the integrity of the hair-cells of the organ of Corti. These cells can no longer generate microphonics when they have degenerated to such an extent that, on subsequent microscopic examination of freshly fixed, well stained specimens, their nuclei are no longer normal in appearance, or when the cells have undergone marked cloudy swelling. Normally, however, the cells are believed to be capable of generating an electric potential between their bases and their free ends, that is to say, perpendicular to the plane of the basilar membrane, as diagrammed in Fig. 133 *A*. When the stapes is displaced in such a way that the basilar membrane moves upward, Fig. 133 *A* shows how a systematic polarization of the hair-cells would cause electrical positivity of the round window and negativity of the oval window. Let us consider in more detail the probable mechanical events in the organ of Corti.

Figure 133 *B* represents a section across the basilar mem-

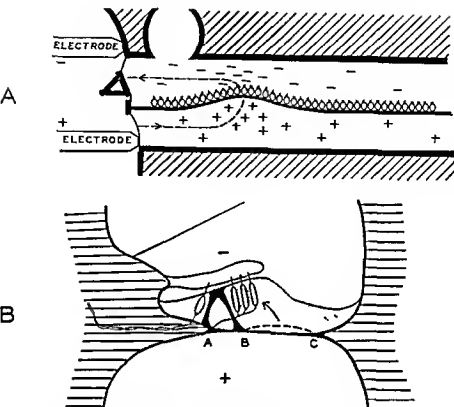


FIG 133 Diagrams of sections through the cochlea

A Longitudinal section showing schematically how an outward movement of the stapes generates a cochlear microphonic due to distortion of the hair cells. The cells are mounted 'in parallel' on the membrane and the potential difference between their ends can be detected by electrodes, as shown. A difference of potential is also detectable between either of these electrodes and another electrode elsewhere on the body of the animal.

B Cross section (drawn to scale from a photomicrograph) showing the arrangement of the sensory cells in the organ of Corti. The one inner and three outer hair-cells are placed on either side of the tunnel formed by the rods of Corti, and their cilia are embedded in the tectorial membrane. When the basilar membrane between the points *B* and *C* is displaced upward by an outward movement of the stapes a distorting pressure is exerted on the outer hair-cells, as shown by the arrow. A strong stimulating sound wave will move the entire organ of Corti about the pivot at point *A* and thereby compress the internal hair-cell as well. The pressure of the stimulus needed to affect the internal hair-cells must be about 50 times as great as that which is needed to stimulate the external cells. The fibers of the auditory nerve are excited during the upward movement of the basilar membrane.

brane, traced from an actual photomicrograph. When the basilar membrane bulges upward or downward, its curvature is probably much sharper across the membrane (Fig. 133 *B*) than along the membrane (Fig. 133 *A*). Furthermore, it seems probable that the triangular structure of the tunnel, formed by the rods of Corti and the portion of the basilar membrane beneath it (*AB* in Fig. 133 *B*), is stiffer than the external portion of the membrane *BC*. Point *A* is rigidly fixed, since it is at the attachment of the basilar membrane to the bony lamina of the modiolus. Point *B* will move slightly upward, as the stapes moves outward, but, at least at low amplitudes of vibration, the chief movement will be a bulging upward between *B* and *C*, as indicated by the broken line in the figure. Such a bulging will cause lateral or oblique compression of the external hair-cells. Movement of the rods of Corti as a unit at higher amplitudes of vibration will compress the internal hair-cell also. The driving force must be about 50 times as great as that needed to stimulate the external cells in order to stimulate the internal cell (cf p. 369). When the membrane bulges downward, all these effects are reversed and the hair-cells are subjected to lateral or oblique 'traction' instead of compression. It is also possible that the tectorial membrane entangles the cilia of the hair-cells and serves to make the cells more sensitive to very slight amplitudes of vibration.

It will be shown in Chapter 16 that the phase of the vibration of the basilar membrane during which the nerve impulses are initiated is the upward swing associated with outward movement of the stapes. According to this present schema, the upward phase of basilar motion is the one associated with compression of the hair-cells. The association of stimulation with compression is in accord with the general behavior of tactile sense-organs, and, furthermore, if we are to accept the theory of excitation of the nerve fibers by a chemical substance (see Chapter 16), it seems more reasonable to associate the liberation of such a substance with compression of the hair-cell than with 'traction' upon it.

This outline of the mechanical events in the organ of Corti

is hypothetical and is suggested merely as a possible mechanism. The mechanism as outlined fulfills one necessary condition, however, in that it shows how the hair cells may undergo one and only one cycle of compression and traction during one cycle of vibration of the basilar membrane. If we assume that the hair cells generate piezoelectric potentials between their upper and lower ends when they are compressed, according to the analogy of the piezoelectric crystal outlined in Chapter 12, we have a possible explanation of the generation of the cochlear microphonics.

It is extraordinary that in the ear the minute mechanical vibrations and tiny pressures involved at threshold should produce sufficient potential to be detected from outside the cochlea. The actual movements may be of molecular dimensions, since the threshold of detectable potential is near the threshold for human hearing and the human ear can hear sounds, at favorable frequencies, which involve movement of the eardrum of less than the diameter of a hydrogen molecule (see p. 56). The minuteness of these amplitudes is compatible with the hair-cell theory, which ascribes the generation of the potential to a semisolid structure, such as a cell containing or ganized, oriented molecules. Furthermore, the external detection of the potential is undoubtedly favored by the parallel orientation of the generating cells, by the favorable electrical circumstances offered by the conducting endolymphatic channels, and by the insulating shell of bone around the cochlea.

Now, the hair-cell theory of the aural microphonics which ascribes the cochlear potential to a piezoelectric effect in the end organ must, if our hypothesis is adequate, satisfy the law of the conservation of energy. We have assumed that the hair-cells behave as electromechanical transducers and convert into electricity the acoustic energy delivered to them. Unlike the nerve fibers, the hair-cells do not supply the energy for the electric response—they merely convert energy from a mechanical into an electrical form. This principle means, then, that no more energy should appear in the form of electricity than is delivered

to the ear in the form of sound. The power-output must not exceed the power input. Although the two energies, acoustical and electrical, cannot be computed exactly, we can show that a reasonable equivalence exists. The argument may be made as follows:

An 800-cycle tone at 60 db above the reference intensity produces an electric potential of about 10^{-4} volt. The power in this sound wave is 10^{-10} watt per square centimeter. Now, this amount of power is delivered to the ear only provided the impedance of the ear is equal to that of air and provided the ear represents a cross-section of 1 sq cm. The impedance of the eardrum at 800 cycles is essentially that of air (see Fig 108, p 261), and the area of the drum in the cat is about 0.5 sq cm. Hence, 5×10^{-11} watt delivered to the eardrum produces a measured potential of 10^{-4} volt. But since power is lost between the eardrum and the cochlea, let us assume that only 10^{-11} watt reaches the organ of Corti. If this amount of energy produces 10^{-4} volt, we can compute immediately the resistance across which this voltage is generated, because in an electric circuit the power P in watts is given by

$$P = E^2/R$$

where E is voltage and R is resistance. Or

$$10^{-11} = (10^{-4})^2/R$$

The value of R , therefore, is 1000 ohms and the question is: does this represent a reasonable value? Direct measurements have not been made, but from the resistances encountered in cellular structures elsewhere in the body it is apparent that this is very nearly what we should expect to be the electrical resistance between the two sides of the basilar membrane. This value is at least of the right order of magnitude to justify our hypothesis that there is an equivalence between the acoustic power delivered to the organ of Corti and the electric power generated by the hair cells.

though they were connected in parallel. But, from the point of view of a pair of electrodes, one of which is on the round window or apex and the other on a relatively distant part of the head, the simple geometrical arrangement of the hair-cells is complicated by several factors, including the spiraling of the basilar membrane. Consequently, the hair cells contribute in no simple fashion to the potential across the recording electrodes. The connection is neither series nor parallel, but a combination of the two. Despite these complicating factors, we may expect that cells near the apex will influence an electrode applied to the apex more than do cells near the base. This expectation depends upon the more favorable position of the apical cells for contributing to a potential measured between the apex and a remote electrode. The reverse must be true of cells near the round window—they contribute most readily to the potential seen at the round window.

At a given frequency, and for low intensities, the form of the pattern of vibration of the basilar membrane presumably remains constant as the sound intensity varies. More or less potential will be generated by each activated cell, but the *relative* contribution of each to the total will remain constant. Increase in the total potential is then due to an increased contribution by each cell. (This situation is quite different from that in a structure composed of units, like nerve fibers, which follow an all or none law. The number of active nerve fibers increases with increasing strength of stimulation, but the potential generated by each unit remains constant.)

Potential as a Function of Sound Intensity How, then, are we to interpret the linear portion of the curves in Figs 125, 126, and 127 relating the potential of the cochlear microphonic to sound intensity? Where there is linearity and a slope of unity, it is implied that over the corresponding range of intensities (*a*) the transmission system delivering energy to the hair-cells is behaving in linear fashion, (*b*) the *relative* distribution of mechanical activity over the basilar membrane remains constant, (*c*) the potential generated by the hair cells is a linear function of their mechanical distortion, and (*d*) no distorting

factors or nonlinear contributions of potential from other sources, such as nerve fibers, have appeared. Experimentally, this linear relation with a slope of unity appears to be the ideal case, and other relations between cochlear microphonics and sound intensity can be regarded as deviations from this ideal relation.

As sound intensity increases, the increase of potential regularly becomes nonlinear when it reaches about 20 per cent of its ultimate maximal value. The appearance of higher harmonics indicates that this distortion is due to nonlinear performance of the transmission system. Ultimately the piezoelectric action of the hair-cells may also become nonlinear.

The mechanical displacement of any segment of the basilar membrane itself is presumably linear at low intensities, but, like all membranes, it ultimately reaches a limit beyond which linearity fails. We do not know whether this limit is symmetrical or unsymmetrical with respect to the position at rest. However, as long as the response of each segment of the membrane is linear, the relative distribution of energy along the membrane will remain constant. As soon as any segment reaches its limit of linearity, the pattern of distribution of activity must change with further increase of intensity. Since the region of the basilar membrane which is maximally disturbed will reach this limit first, the pattern of the disturbance will change when this limit is reached. The limit of linearity essentially represents a point of diminishing returns beyond which the amplitude does not keep pace with an increase in the displacing force. Therefore, after the maximum of the disturbance on the membrane has reached this limit, the disturbance on either side of the maximum will grow more rapidly than the maximum itself. Now, since the form of the over all resonant properties of the ear is imposed upon this process, it is plainly possible that the relative increase on the two sides of the maximum may not be equal, and the disturbance may become skewed. The skewing would represent a shift of the maximum to a new position and a consequent change in the apparent pitch of the tone. We have in these notions a hypothetical explanation of the change of

pitch with intensity (see Chapter 3), as well as a possible explanation of certain anomalies in the behavior of the cochlear microphonics

The Combination of Action Potentials with the Cochlear Microphonics The action potential appears as a secondary wave in the electrical output of the cochlea. The action potential is made up of many nerve impulses, more or less synchronized, all of which exhibit approximately the same time-course and the same potential. Each nerve fiber has a threshold which probably corresponds to some finite degree of distortion of the hair cell to which it is attached, and each is all or none in its response. The effect of each fiber on the recording electrodes varies, of course, with the distance and orientation of the fiber.

The action potentials and the cochlear microphonic may combine to give an electric potential either greater or less than the microphonic alone. The variability encountered depends upon the nonsinusoidal shape of the action potential and on changes in the phase relation between microphonic and action potential with change of the frequency of the stimulus (see Fig 124, p 317)

In the curve expressing the combined electrical output of microphonic effect plus action potentials as a function of intensity, we may find slopes either greater or smaller than unity. At intensities slightly above threshold, we may expect a very rapid growth of the action potential component, for such increases have actually been observed in the eighth nerve at low intensities. If the action potential reinforces the microphonic effect, a slope greater than unity will result. If it interferes with the microphonic effect, the result will be a slope of less than unity, as in the section of curve *C* in Fig 126 which lies between 35 and 50 db (p 320). On the other hand, at higher intensities the action potential may cease to grow at a rapid rate, and if the action potential is interfering with the microphonic effect, the interference will then become less pronounced at higher intensities. In that event, increase in intensity will give a slope greater than unity, for the curve will be rising toward the ideal curve of pure microphonic effect, which would

have been followed had it not been for the interference from the action potential. This is probably the basis of the abrupt rise in curve *C* of Fig. 126, between 55 and 65 db.

There are other possible causes of deviation from a linear slope, and in general they tend to give slopes of less than unity. Among these are (a) Reflex contractions of the intra-aural muscles. The tensor tympani and the stapedius contract in response to stimulation by sound and reduce the transmission of tones below 1000 cycles (p. 264). The threshold for this effect is about 30 db above the threshold of hearing (Lorente de Nó, 1). It is most improbable, therefore, that the reflex should appear at very low intensities, or after the spontaneous activity of the middle-ear muscles has been reduced by application of chloroform. At frequencies above 1000 cycles, moreover, the transmission of sound is not affected by this reflex. (b) A constant error in the measurement of the size of the potential due to background noise. This error is obviously important for the very low amplitudes of response near threshold. (c) All the deviations from linearity due to arrival at limits of linearity, whether in the middle ear, the inner ear, or in the generation of electric potential in the individual hair-cells. All these factors impose a limit to the electric response and cause nonlinearity of the response-curve for high intensities of stimulation.

TINNITUS

If the nerve fibers of the auditory nerve are stimulated by any means whatever, we should expect to experience an auditory sensation. In fact, the most satisfactory explanation of most cases of the persistent ringing in the ears called *tinnitus* is that certain hair-cells, or the nerve fibers connected with them, become hyperirritable and discharge nerve impulses more or less continuously as a result of some pathological process. This abnormal condition may be acute and temporary, as the result of excessive stimulation by a loud sound, or it may be chronic. The condition which underlies the almost universal degeneration of hair-cells and ganglion cells near the oval window with advancing age (Chapter 2) may well involve a temporary stage

of hyperirritability. This hypothesis would explain the usual high pitch of mild chronic tinnitus, for, as we shall see in the next chapter, it is the nerve fibers ending in the lower part of the basal turn of the cochlea which evoke auditory sensations of high pitch. This hypothesis is attractive, but it is not to be taken as a universal explanation of all tinnitus, for some cases are undoubtedly due to irritation of the higher auditory pathways and centers within the brain.

ELECTRICAL STIMULATION OF THE COCHLEA

Finally, as an aid to the understanding of the nature and origin of cochlear microphonics, let us consider a reverse phenomenon—the *electrophonic* effect. The ear behaves as an electromechanical transducer when it converts sound waves into the electrical waves which we call microphonics. Like most other transducers, it is also capable of the reverse process, and, when an alternating electric current is passed through the head, we hear a tone whose pitch is determined by the frequency of the current (see p. 65). Presumably, then, the ear converts alternating currents into mechanical vibrations, as well as mechanical vibrations into alternating currents.

The hair cell theory of the origin of the cochlear microphonics offers reasonable explanation of the perception of a definite pitch when a normal ear is stimulated electrically. We have assumed that the hair cells act as electromechanical transducers, converting mechanical into electrical energy. In this respect they are analogous to piezoelectric crystals. It is natural to extend the analogy and to suppose that in the hair-cells, as in piezoelectric crystals, the process is reversible and that, under the influence of an electric field the cells tend to alter their shape. Therefore, as the electric field changes periodically, the basilar membrane is made to vibrate. The portion of the basilar membrane which, by virtue of the physical constants of the auditory mechanism (mass, stiffness, and resistance, cf. Chapter 10), is preferentially responsive to the particular frequency of the stimulating current will vibrate with the greatest amplitude.

As a result of the mechanical vibration, nerve impulses will be initiated in the appropriate fibers in the usual fashion

It should be clear that this hypothesis does *not* involve selective *electrical tuning* of the organ of Corti. The energy is delivered to the ear electrically, but is transformed into mechanical vibration. The 'tuning' itself is purely mechanical.

Of course, we cannot, as yet, be completely certain that the mechanical vibrations are initiated by a piezo effect in the hair cells. It is possible that some other structure within the ear possesses a residual charge, due to a process of polarization, so that the structure is made to vibrate when immersed in an alternating electric field. The action, in this case, would be of the sort characteristic of a condenser microphone. We may be certain, however, that, regardless of the structure responsible for the vibrations, the fact that the perceived pitch is related to the frequency of the alternating current is due to the mechanical 'tuning' of the cochlea.

If the electric current stimulated the auditory nerve directly, we should not expect to discriminate the frequency of the current. All frequencies should then sound essentially alike—they should all sound like noises. Such, in fact, was the finding of Andreef, Gersuni, and Volokhov when they stimulated people whose cochleas were destroyed but in whom the auditory nerve was still able to function. These people were unable to distinguish between different frequencies when the auditory nerve was stimulated by an electric current, and all frequencies sounded like a noise.

The tones heard by the electrical stimulation of normal ears lack the purity of tones heard in the usual way. When listening to a sinusoidal electric current, one hears the higher harmonics very prominently. In fact, some observers are able to identify the pitch of a tone as an octave higher than the stimulus-frequency. And when two currents of 1000 and 1700 cycles are led simultaneously to the ear, a difference tone of 700 cycles appears which sounds louder than either of the two primary tones. Obviously the electrophonic phenomenon is subject to considerable distortion.

The severity of the distortion introduced with electrical stimulation can be demonstrated by the simple procedure of connecting the electrodes on the observer to the output circuit of a radio set. Music can be heard and popular tunes identified, but the quality is definitely poor—'tin pan' music. Speech can be easily recognized as speech, but only occasional words can be understood (Stevens, 8). Clearly, electrical stimulation does not promise much as an alternative means of hearing so long as so much distortion is present. We should like, if possible, to be able to account for this excessive amount of distortion which is experienced under electrical stimulation. Distortion may arise from two causes. First, since the moving elements of the ear do not strictly obey Hooke's law, harmonics may arise from stimulation by a sinusoidal mechanical force. This fact is believed to account for the normal amount of distortion introduced when the stimulus is a sound wave. It appears unlikely, however, that this type of nonlinearity in the auditory mechanism is able to produce all the distortion observed under electrical stimulation. Hence, a second cause must operate, one which appears to be electrical rectification.

Electrolytes bounded by various types of surfaces are known to behave as complete or partial rectifiers, in that a current passes the boundary more easily in one direction than in the other. An electrolytic condenser is an example of this phenomenon. Furthermore, whenever rectification of a sinusoidal current takes place, the resultant current can be analyzed into a steady component, the original frequency, and a series of harmonics. Therefore, if partial rectification of the current sent through the ear were to occur at some boundary, we should have reason to expect the large distortion which was actually observed. On the assumption that some of the distortion is due to electrical rectification, it is to be expected that, when a high frequency modulated current is passed through the head, sufficient demodulation would occur to allow the ear to hear the modulating frequency. A frequency of 100 kilocycles was modulated by a 400-cycle wave and passed through the head of an observer, with the result that the observer heard a 400-cycle tone (Stevens and

Hunt). This experiment demonstrates that the ear can respond directly to a radio wave, provided the modulated radio-frequency is conducted through the head at a sufficient intensity. Tests show that some of the rectification accompanying the electrophonic phenomenon occurs at the electrodes (one in the external ear—the other elsewhere on the body) through which the current is applied. Measurement of this part of the rectification discloses, however, that it is too slight to account for the observed effects, in stimulation either by audio-frequencies or by radio-frequencies. There appears to be an additional and large rectifying action taking place in the ear itself, which, of course, occupies only a small part of the total conducting path between the electrodes.

CHAPTER 15

THE LOCALIZATION OF FREQUENCY RECEPTION ON THE BASILAR MEMBRANE

IN PREVIOUS chapters we have seen why, from physical considerations of the anatomical structure of the inner ear, we should expect the basilar membrane to vibrate more vigorously near the helicotrema in response to low tones and near the round window in response to high tones, and we have considered some experimental evidence from the study of the cochlear microphonics which indicates this type of 'tuning' within the ear. This notion of selective vibration is fundamental to an understanding of frequency discrimination and sound analysis by the ear, and we shall therefore consider more thoroughly the evidence for localized disturbances within the cochlea. First, from a study of the effects of loud sounds, we shall see that the basilar membrane actually does vibrate in response to sound. Then, we shall see what regions are preferentially activated by particular frequencies and how such activation correlates with the facts relating to pitch discrimination.

THE EFFECTS OF LOUD SOUNDS

It is a matter of common knowledge that a very loud sound produces sensations of discomfort, amounting to acute pain, and leaves the ear temporarily deaf and with a persistent ringing, known as *tinnitus*. Very violent explosive sounds may even cause permanent deafness. In addition, the wave of pressure in the vestiblymph and perilymph set up by a sudden, very loud sound may be sufficient to stimulate the sensory cells of the semicircular canals, the utricle and the saccule. The subjective sensation is then one of vertigo, or of a sudden displacement in space—a jolt. The reflex response to such stimulation is a sudden movement of the head, such as normally

tends to compensate for an actual sudden change of position in space (Tullio, Békésy, 20) The direction and character of the movement depend upon which of the labyrinthine sense organs are most strongly stimulated This movement is not to be confused with the orienting reflex in which the head is turned toward the source of sound The movements from direct labyrinthine stimulation are parts of the complex pattern of righting reflexes, evoked in this instance by an abnormal mode of stimulation For our present purposes their interest is merely that they show the violence of the pressure waves generated in the inner ear by very loud sounds

Long-continued exposure to noise of considerable intensity is reputed to be a cause of deafness The term, *boiler maker's deafness*, was coined to express this association of deafness with an occupation involving such exposure Adequate pathological studies of human ears deafened either by acute accident or by long-continued exposure to noise have not been made, and we shall not attempt to describe the few cases that have been examined Animal experimentation has, however, provided a fairly complete picture of the nature of *detonation-deafness*

In the cochleas of guinea pigs exposed to the sound of revolver shots at close range, Guild (1) recognized, at post mortem examination, degrees of damage ranging from a loss of some of the external hair-cells, with or without derangement of the supporting cells, to cases in which the external hair-cells were all absent, the organ of Corti badly broken, and the inner hair-cells absent as well The distribution and the severity of injury varied from animal to animal, but tended, on the whole, to center at the middle of the cochlea Occasionally there were regions of serious injury adjacent to the stapes and round window The more severe injury near the center of the membrane tended to shade off gradually, through lesser degrees of injury on either side, to more or less normal organ of Corti toward the ends of the basilar membrane

In another type of extensive injury, produced by brief exposure to a very loud tone (Stevens, Davis, and Lurie), part of the organ of Corti external to the tunnel becomes completely

detached from the basilar membrane, although the membrane itself and its arteries remain intact (see Fig 134). As was true for Guild's animals, the internal hair-cells, although not detached from the basilar membrane, were usually severely damaged.

These lesions show, beyond a doubt, that the basilar membrane does actually vibrate violently in response to strong

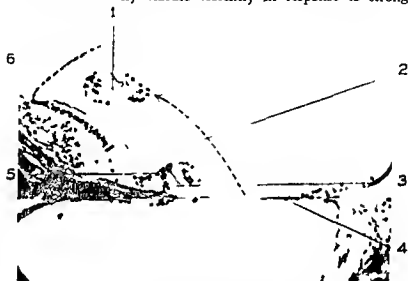


FIG 134 Section of the cochlea of a guinea pig which had been exposed for 5 minutes to a tone of 400 cycles at 125 db above threshold. The intraural muscles had previously been rendered inactive by the local application of chloroform. Following exposure to the tone the threshold of the cochlear microphonics was elevated by 50 to 70 db throughout the audible range.

The outer portion of the organ of Corti (1) has been dislodged and knocked into the upper left hand corner of the scala media. The basilar membrane (4) is still intact and so are Reissner's (6) and the tectorial (2). The internal hair-cell (5) is still in its normal position although the tunnel (3) has been partially disrupted. (After Stevens, Davis and Lurie.)

sounds. The basilar membrane itself is apparently capable of withstanding violent mechanical agitation, but the organ of Corti is more vulnerable. Furthermore, the external hair-cells seem to be in a more exposed position than the internal cells. It is a curious fact that the external hair-cells also seem to be the more vulnerable to drugs, toxins, and the effects of advancing age (Lurie, 1).

THE PLACE THEORY OF FREQUENCY RECEPTION

We recognize in sounds an attribute which we term *pitch*. Pitch correlates *approximately* with the frequency of the sound waves falling upon the ear. The fact that we can differentiate sounds with respect to this attribute (cf. Chapter 3) implies that there is some difference in the pattern of nerve impulses passing up the eighth nerve when the ear is stimulated by high as opposed to low frequencies. There have been, in general, two schools of thought as to the nature of this difference. One school has assumed that different groups of nerve fibers are activated by high and by low tones respectively, the other that the fundamental difference in the pattern of neural events lies in the frequency of nerve impulses, irrespective of the particular fibers which may be involved. The first theory ascribes the discrimination of frequency to the analysis of sounds by the sense-organ itself, the second theory simply passes the problem of analysis along to the central nervous system without resolution.

One obvious principle by which physical systems can discriminate between mechanical vibrations of different frequencies is that of resonance. This principle is that, when a series of structures of different natural periods of vibration are exposed to a force of a particular frequency, the one whose natural period corresponds most nearly to that frequency will vibrate with the greatest amplitude. If there were in the inner ear a set of resonators tuned to different frequencies, we should have an adequate explanation, in physical terms, of sound analysis, and hence of pitch discrimination. If the analysis is carried out in the central nervous system, we have no explanatory principle to offer, since there is nothing in the central nervous system which has the appearance of a set of tuned resonators, either mechanical or electrical. Helmholtz was guided by this general principle when, following the lead of earlier writers such as Bell and Cotugno, he elaborated his famous theory of pitch discrimination. Helmholtz suggested that the rods of the organ of Corti were the vibrating elements, but he later ascribed the response to the fibers of the basilar membrane. The systematic anatomical differences between

the upper and lower ends of the basilar membrane with respect to its width and also to the size of the various structures of the organ of Corti attached to it, described in Chapter 10, were cited in support of this hypothesis

Now, the evidence to be considered in this chapter demonstrates that the auditory mechanism behaves, to some extent, as if it were a resonant analyzer of the sort envisaged by Helmholtz. A maximum of disturbance occurs on the basilar membrane at different places for stimuli of different frequencies. That much appears certain. That the maximum results from the operation of the simple principles of resonance, however, is extremely questionable. The damping of the cochlear system is presumably too great for it to behave in a way analogous to a row of resonators, such as we have in the strings of a piano. Consequently, the simple resonance theory of frequency reception must be regarded as an oversimplification, and we must look to other principles for an explanation of the fact that a particular tone activates a particular region of the basilar membrane. In other words, the terms *resonance theory* and *place theory* are not necessarily synonymous. In Appendix II is a set of principles suggested to underlie the behavior of the cochlea and to make possible a place theory, while forsaking the principle of simple resonance.

Our purpose in this chapter will be to examine the evidence for the proposition that different areas of the basilar membrane respond specifically to different frequencies—in accordance with a place theory.

EVIDENCE FROM LONG EXPOSURE TO LOUD TONES

Wittmaack, and others following him, exposed guinea pigs to the sound of a bell, a whistle, or a pipe, either continuously or for a certain period each day for many days, and then examined the inner ears for pathological changes. Their guiding motivation was to find a correlation between the frequency of the tone used and the location on the basilar membrane of a region of degeneration. It was tacitly assumed that selective response of the basilar membrane would lead to destruction of

the organ of Corti only in that region of the basilar membrane activated by the exposure-tone. Unfortunately, the reports of the various investigators (cf. Kemp) are often at variance with one another and do not lead to clear conclusions.

More recently, experiments of this type have been combined

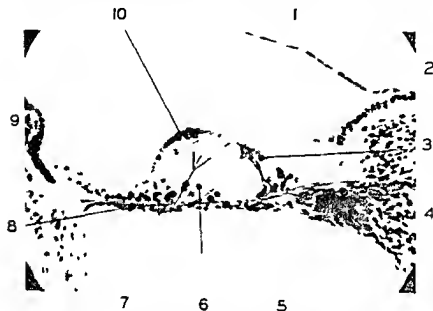


FIG 135 Degeneration of external hair-cells produced by long exposure to a loud tone. The guinea pig was exposed continuously for 45 days to a tone of 2500 cycles at 106 db above human threshold. The section is from the middle of the second turn. The external hair-cells have degenerated completely, but the internal hair-cell is still present and apparently normal. The spiral ganglion of Corti appears to be normal.

- | | |
|-------------------------------------|--------------------------------------|
| 1 — Reissner's membrane | 7 — degenerated external hair-cells, |
| 2 — tectorial membrane | the nuclei have entirely dis- |
| 3 — nucleus of normal internal hair | appeared |
| cell | |
| 4 — nerve-cells of spiral ganglion | 8 — basilar membrane |
| 5 — tunnel | 9 — stria vascularis |
| 6 — supporting cells | 10 — Hensen's cells |

(Davis, Derbyshire, Kemp, Lurie, and Upton, unpublished)

either with tests of hearing of a functional sort, based upon conditioned reflexes, or with tests involving the electrical activity of the cochlea. A dog was conditioned to withdraw his leg when any musical note was presented (Finch and Culler). His

normal threshold curve was determined by this method and he was then exposed to intense tones for various periods. Eighteen hours of exposure at 3000 cycles caused loss of hearing of 40 to 50 db in all parts of the auditory range between 200 and 5000 cycles. Subsequent exposure to a tone interrupted 52 times per minute caused still further loss of hearing.

Intensities of stimulation approximately 100 db above threshold are usually required to produce a lesion of the cochlea in guinea pigs (Davis, Derbyshire, Kemp, Lurie, and Upton). With such intensities at a frequency of 2500 cycles, degeneration of the external hair cells occurs, as shown in Fig. 135. The degeneration regularly centers in the middle of the second cochlear whorl, i.e., near the middle of the basilar membrane. The sensitivity of a number of such animals was determined by measuring the threshold of the aural microphonics. Moderate impairment was found, but the loss centered at 1200 cycles rather than at the exposure tone of 2500 cycles. The loss of sensitivity corresponded reasonably with the severity and extent of the histological lesion.

The greatest elevation of threshold for the cochlear microphonics does not necessarily correspond to the frequency of the stimulating tone which produced the damage. It is therefore unsafe to assume that deafness due to exposure will be specific for the frequency of the exposure tone. There appears to be systematic displacement of the position of damage in the direction of the greatest sensitivity of the ear, that is, toward the middle of the auditory range, but this point requires further experimental investigation. These facts, and also the extensive damage caused in some experiments by brief exposure to very loud tones, indicate that at high intensities of stimulation a wide area of the basilar membrane is set into violent agitation. The wide extent of the effect renders degeneration by excessive stimulation useless as a method for locating the specific regions of the basilar membrane which may be responsive to particular frequencies. Nevertheless, many of these experiments did show localized regions of degeneration, and, when a restricted loss of sensitivity was detected by the electrical method, it

correlated in general with such a localized region of degeneration

THE INJECTION OF DRUGS

Experiments based upon the injection of drugs into the cochlea through the round window or the placing of toxic substances, such as sodium chloride or cocaine, on the round window membrane (see p 337) lead to a similar conclusion histological damage to the sensory cells of the organ of Corti near the round window is associated with an elevation of the threshold for cochlear microphonics at high frequencies of stimulation

EVIDENCE FROM HUMAN PATHOLOGY

Two clinical forms of deafness encountered in man are associated with more or less clearly defined degenerations of the organ of Corti or of the auditory nerve fibers associated with particular regions on the basilar membrane

Gradual High Tone Deafness The first of these, already described in Chapter 2 (Fig 22), is the progressive loss of hearing for tones of high frequency which occurs with advancing age In this type of deafness, sensitivity falls off gradually with increasing frequency of the test tone This condition is correlated with partial atrophy of the auditory nerve supplying the basal turn of the cochlea (Crowe, Guild, and Polvogt)

Abrupt High Tone Deafness In the other, less common, form of high tone deafness the audiograms show much more abrupt breaks, as illustrated in Fig 20 (p 61) and in Fig 136, which may be correlated much more precisely with the atrophy of auditory nerve fibers and the degeneration of the organ of Corti found post mortem Histological study (Crowe, Guild, and Polvogt) of 79 ears of this type proved quite conclusively that the receptors for high tones are located in the basal turn of the cochlea More specifically, a statistical analysis of the data (Ciocco) shows that the lower end of the area receptive to 2048 cycles is more than 95 mm and less than 12 mm from the basal end The upper boundary of the area for 4096

cycles is definitely more than 73 mm and less than 95 mm from the basal end, and the region sensitive to 8192 cycles is apparently located approximately 5 mm from the end. Figure 136 presents the audiogram and Fig. 137 a graphic summary of the abnormalities of one of these ears.

There are exceptions in this series of observations, in which the abrupt type of loss is not associated with a sufficient degree of nerve atrophy to explain the impairment of hearing which was measured ante mortem. In approximately one fourth of the ears no lesion was found in either the middle or inner ear that adequately explained the hearing loss. These ears have

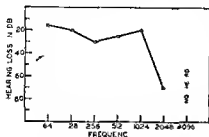


FIG. 136 Audiogram showing abrupt high tone deafness (After Crowe, Guild and Polvogt)

less impairment of hearing than the group as a whole, and it is possible that their losses were due to early organic changes in the cochlea which the histological technique was not adequate to demonstrate. On the other hand, the impaired hearing in these ears may have been due to lesions of the central auditory pathways. These studies show, incidentally, that nerve atrophy does not necessarily precede atrophy of the organ of Corti. There is apparently a nutritional relationship between the external sulcus cells and the sensory cells, since atrophy of the former usually precedes that of the latter. No etiology for high tone deafness can be suggested here, but the observations are of great theoretical importance for the understanding of the mechanism of hearing since they are apparently the only ones in which a correlation has been made between anatomical changes in the sense-organ of an individual and quantitative studies of his subjective hearing.

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EVIDENCE FROM THE COCHLEAR MICROPHONICS

As we have already seen (Chapter 13), measurements of the cochlear microphonics show that the cochlea is differentially

'tuned,' i.e., one end responds preferentially to low tones and the other to high tones. The only reasonable interpretation is that the electromechanical activity associated with the low tones is located in a position more favorable for detection by the electrode at the apex, and that the activity in response to high tones

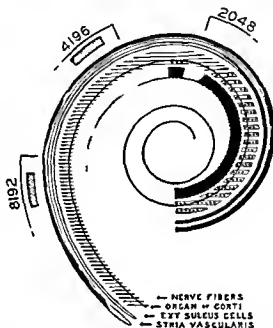


FIG. 137 Chart of the pathological changes in the basal turn of the human ear whose audiogram is shown in Fig. 136. The transition from normal to abnormal is unusually abrupt in this case.

Inner spiral, nerve-fibers, black = normal, white = degenerated

Second spiral, organ of Corti, rectangle with large dots = organ of Corti with normal hair-cells, plain line = organ of Corti degenerated.

Third and fourth spirals; black = normal and white = abnormal external sulcus cells and stria vascularis respectively.

Outside the spirals are indicated the limits of the zones required for the reception of frequencies 8192, 4196, and 2048. The most probable locations for 8192 and 4196 are indicated by the shaded rectangles. The locations are based on an analysis of the abnormalities of 79 human ears and their audiograms (After Crowe, Guild, and Polvogt.)

is located nearer to the round window. The relation is the same in the guinea-pig and in the cat. It is illustrated in Fig. 123 (p. 314) by the crossing of the threshold curves for the microphonics when the 'active' electrode is moved from the apex to the round window.

A much more precise correlation of location on the basilar membrane with frequency has been made by drilling into the cochlea and producing local mechanical disruption of the organ of Corti (Stevens, Davis, and Lurie). The thresholds of the aural microphonics to various frequencies of stimulation were determined before the operation and were again determined immediately afterwards. In some cases a general loss of sensitivity ensued, but usually the threshold of the microphonics remained, within the limits of observational error, unaltered at most frequencies. The threshold for certain frequencies, however, was elevated, and, as a rule, the transition between normal sensitivity and reduced sensitivity was sufficiently abrupt to be located within a half octave on the frequency scale. The

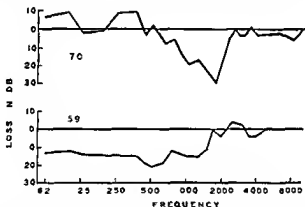


FIG. 138. Electrical audiograms of guinea pigs showing loss of sensitivity following local surgical damage to the cochlea. No. 59 shows a loss to low tones. No. 70 shows a loss in the middle range without loss at either extreme. (From Stevens, Davis, and Lurie.)

cochleas were subsequently examined histologically, and the transition between normal and abnormal organ of Corti was found to be fairly sharp. In most instances, the transition could be located to within about 1 mm.

Illustrative audiograms, showing the differences between the threshold curves taken before and after the operative damage are shown in Fig. 138. In general, complete destruction of part of the organ of Corti does not elevate the threshold for

any tone by more than 30 db. This is true even when more than half the organ of Corti is destroyed, and suggests that there is a wide spread of the disturbance on the basilar membrane. The spread of vibration is apparently greater for low than for high tones. In the audiograms of Fig 138, the points at which the response departs abruptly from normal correlate with the boundaries between functional and nonfunctional hair-cells. Thus, number 59 in Fig 138 shows a sharp drop at 1750 cycles and depression of all tones below that frequency. Number 70 shows a departure from normal at about 600 cycles and also at about 2250 cycles. Such departures were correlated with the location of histological damage to the organ of Corti.

Figure 139 summarizes the results of this series of experiments on guinea pigs. Position on the basilar membrane is represented along the ordinate and frequency along the abscissa. Each rectangle correlates the border of a lesion with an abnormality in an audiogram. The width of the rectangle indicates the range of frequency within which the deviation from normal sensitivity occurred, and its height represents the width of the zone on the basilar membrane separating definitely normal from definitely abnormal hair-cells. The circles correlate the centers of isolated depressions in the audiograms with the corresponding circumscribed zones of damage to the hair-cells. The band determined in the chart by the rectangles and circles therefore indicates the positions on the basilar membrane at which tones of various frequencies are received when they are near the threshold of audibility.

Relation to Human Frequency Discrimination The solid curve in Fig 139 was not drawn to represent the curve best fitting the rectangles and circles. The solid curve was obtained independently from an integration of DL's for frequency, as measured in human ears (see p 94). The data given by Shower and Biddulph were integrated at the sensation level of 40 db and plotted on a scale (right hand ordinate scale of Fig 139) which was adjusted to make its total length correspond to the length of the basilar membrane. Integration of DL's at other sensation levels or loudness levels would give a different

value for the total number of DL's in the audible range, but the *form* of the curve relating them to frequency would be essentially similar to that in Fig 139 (cf Fig 35, p 96). In making this adjustment of scales we assume that the minimal detectable difference in frequency corresponds to the minimal detectable distance between two adjacent regions of excitation

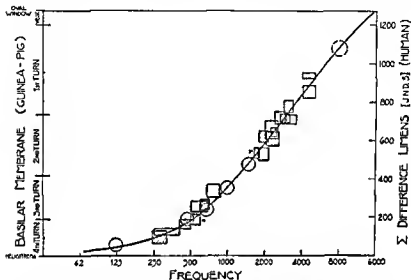


FIG 139 The correlation between the position of damage along the basilar membrane and the associated changes in the audiograms. The width of each rectangle represents the frequency range within which the deviation from normal sensitivity occurs, and its height represents the zone on the basilar membrane separating definitely normal from definitely abnormal hair-cells. The centers of the circles indicate the centers of peaks or depressions in the audiograms and the centers of isolated normal regions or zones of damage of the organ of Corti. Numbers refer to the audiograms shown in Fig 138. The solid line represents the integration of Shower and Biddulph's data for human pitch-discrimination as explained in the text. (From Stevens, Davis, and Lurie.)

on the basilar membrane, and that this distance is constant throughout the length of the cochlea. This is a reasonable assumption, since the hair-cells are distributed rather evenly along the membrane. The striking correspondence between the results of experimental destruction of parts of the cochleae of guinea pigs and the evidence derived from psychological

determinations of the capacity for the discrimination of pitch testifies to the validity of both methods

The integration shown by the curve in Fig 139 indicates that the human ear can distinguish, at the sensation level of 40 db, about 1300 tones between the lowest and the highest audible frequencies. Since integration at higher levels yields a greater number (p 94), we may take the number 1500 as a more representative figure. This value means, in terms of our earlier assumption, that two tones can be differentiated in perception provided they stimulate patches on the basilar membrane differing in position by 0.02 mm. This compares with an approximate sensibility of 1 mm on the tip of the tongue and 2.3 mm on the finger tips. There are approximately 2500 internal hair cells in the human cochlea, and it is interesting to note that 0.02 mm on the basilar membrane is almost the distance occupied by two internal hair-cells. The significance of this observation lies in the fact that a single nerve fiber connects with one or two hair cells (cf Chapter 10). This type of innervation suggests that, in order to account for pitch discrimination, the number of hair-cells should exceed the number of discriminable differences. Hence, the relation of approximately two internal hair cells to one DL appears reasonable.

The internal hair cells, since they are rather simply innervated, should be responsible for pitch discrimination at its best. On the other hand, the location of the internal cells at the edge of the basilar membrane, in a region relatively protected from mechanical agitation, suggests that their threshold should be higher than that of the external cells. Direct evidence for this notion was obtained from one animal, a cat, which showed 30 to 40-db hearing loss for all tones and which upon examination revealed degeneration of the external cells only (Stevens, Davis and Lurie). The fact that the threshold for internal cells appears to be from 30 to 40 db above that for the most sensitive external cells suggests an explanation for the finding of Shower and Biddulph (cf Fig 31, p 88) that differential sensitivity to frequency is much less near threshold than it is for tones 40 db above threshold. Indeed, an integra

tion of the DL's obtained at 5 db above threshold yields about 500 discriminable tones as against 1300 at 40 db. In other words, the multiple innervation of the external hair cells (several hair cells innervated by one fiber and several fibers connecting with each hair cell) appears to be reflected in poorer differentiation of tones when the tones are so weak that the external cells alone are activated.

Finally, we have in Fig. 140 a representation of the position along the basilar membrane of maximal sensitivity to various frequencies. The locations given in this figure for the reception of high tones by the human ear are entirely consistent with the positions ascribed to them by Crowe and his associates.

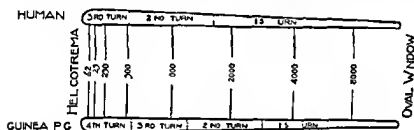


FIG. 140 The localization of frequency reception on the basilar membranes of man and guinea pig. (From Stevens, Davis, and Lurie.)

(p. 363) The lower octaves are greatly crowded at the apical end of the cochlea. This crowding explains the difficulty encountered by most efforts to prove localized response of the basilar membrane to low tones and it also explains why the differential sensitivity of the ear is relatively poor at low frequencies.

Further Evidence from Animal Experimentation The method employed in the experiments described above suffers from one obvious criticism. The cochlea has been damaged by entering it. It is always possible that the anatomical derangement has altered the mechanical characteristics of the system and thereby altered the position of maximal sensitivity on the basilar membrane to a particular tone. Cullen has reported a series of experiments on the guinea pig free from this defect. His procedure was to record the microphonics of the cochlea

from twenty-five different points on its external surface and to determine the intensity of stimulation necessary to obtain an arbitrary but very small response at various frequencies. For each point a particular frequency could be found which gave the arbitrary threshold response at a lower intensity of stimulation than was necessary for any neighboring point. This finding indicates that the microphonic for that particular frequency of stimulation is generated near the point in question. The results of Culler's experiment are plotted in Fig 141. In this representation, the cochlea appears coiled as though viewed

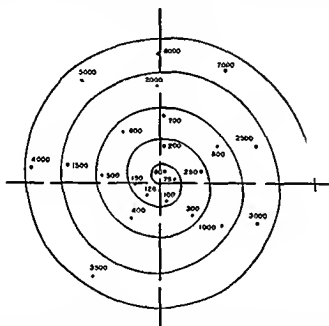


FIG 141. The optimal positions in the guinea pig for detection of the cochlear microphonics near threshold at the frequencies shown. The cochlea is represented as a spiral viewed from a point on its axis. The nucleus is at the center. (After Culler)

from a position along the axis of the spiral. The various maps of the cochlea agree quite well with one another, although the relative crowding of the lower octaves into a small space toward the apex of the cochlea is less extreme in Culler's map. A possible factor in Culler's method is that the lines of current-flow may be deformed by variation in the thickness of the bony wall

of the cochlea and the locations of certain points systematically displaced for this reason. All our present evidence taken together would indicate that Culler's points are all slightly displaced in the direction of the round window. Nevertheless, we may conclude with certainty that a weak tone of given frequency activates selectively one particular region of the basilar membrane whose location is expressed by a map having the general features of the maps in Fig. 140.

Other studies by the electrical method following the production of local surgical lesions give confirmatory evidence in the form of a gross localization. High tones are localized toward the round window and low tones toward the apex, but in most of these experiments the localization of particular frequencies was not precise. The lack of precision is reasonably explained by the fact that these other studies employed intensities of stimulation far above threshold. Apparently, localization of activity is sharply confined only at threshold, and the area of vibration spreads extensively up and down the basilar membrane as the intensity is increased.

THEORIES OF FREQUENCY DISCRIMINATION

It is unreasonable, of course, to suppose that a single hair cell is ever stimulated separately. There is always some spread of excitation along the basilar membrane, and, at high intensities, the spread may cover the entire length of the cochlea. How, then, are we to account for the remarkable ability of the ear to resolve small differences of frequency? Certainly there must be some principle by which one broad pattern of stimulation can be distinguished from another very similar one, which is displaced only 0.02 mm from the first.

One possible principle is that of *maximal stimulation* (Wilkinson and Gray). Presumably, every pattern of basilar activity has at least one maximum where excitation is greater than at points on either side. The position of this maximum may determine the pitch of a tone. Where several maxima occur, due to a complex sound, the ear is able to distinguish the several

components of the sound. This principle has been tacitly assumed in most efforts to explain auditory phenomena.

Objections have been raised against the principle of maximal stimulation on the grounds that the maxima are not sharp, that sometimes two tones can be heard when there is reason to believe that only one maximum exists, and that, in low tones, pitch may be perceived even though it is probable that the pattern of excitation has no true maximum at all. In an effort to circumvent the first two of these objections Békésy (4) pointed to an experiment by Mach in which it was shown that, when a visual field contains two levels of brightness with a gradual transition from one level to the other occurring in the

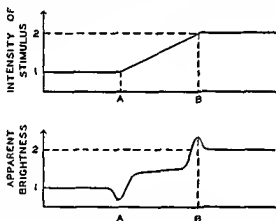


FIG. 142. Showing how an abrupt change of gradient in a visual stimulus produces a salience in sensation. A stimulus whose intensity varies from level 1 to level 2 produces the appearance of a dark ring at *A* and a bright ring at *B*.

region separating the two levels, a bright and a dark ring can be seen where we should expect to see *only* the beginning of a smooth change in brightness. This effect is illustrated schematically in Fig. 142. The stimulus changes linearly from level 1 to level 2, but the observer perceives a dark ring at *A* and a bright ring at *B*. Békésy also pointed out that, when a stimulus of the form shown in Fig. 143 is pressed against the skin of the arm, it produces the impression of an object having two ridges, as shown in the same figure. These facts suggest that when a sensitive surface of the body, either in the eye or on the skin,

is subjected to a stimulus in which there is a change of gradient from place to place, the change of gradient stands out prominently in sensation. If we regard the basilar membrane as such a sensitive surface of the body, we might expect to find a similar effect—an effect which would make the relatively sharp change of gradient in excitation at the maximum of a basilar disturbance stand out in sharp contrast to the rest of the disturbance.



FIG 143 Showing how a change of gradient affects the sensation produced by a tactual stimulus

The application of this principle of gradients to the case of stimulation by two tones which are near together in frequency and which stimulate overlapping regions on the basilar membrane is illustrated in Fig 144. The two excitations sum to give a rather flat topped pattern of stimulation in which there are two sharp changes of gradient. At each of these places we should expect the sort of salience depicted by the dotted curves in the figure. As an instance in which this principle offers interesting possibilities for explanation, we may recall the experiment by Youtz and Stevens, in which they found that an observer can identify the components of a frequency modulated tone when the components are spaced apart by only 8 cycles (see p 241).

It has been urged that the principle of maximal stimulation cannot apply to the perception of the pitch of low tones, because a frequency near the lower limit of hearing is supposed to stimulate the basilar membrane as vigorously immediately at the helicotrema as at a short distance away. We have no direct evidence that such is the case, but, assuming it to be true, we might still conceive how one low tone could be distinguished from another by reason of its pattern of stimulation. The principle of gra

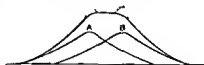


FIG 144 The summated excitation due to the individual disturbances *A* and *B* undergoes a change of gradient at two places and gives rise to the two saliences shown by the dotted curves

dients could presumably apply to the situation represented in Fig 145, in which there is no genuine maximum, but in which there is an abrupt change of gradient whose position depends upon the frequency of the stimulating tone. The obvious difficulty with this theory is that we have, as yet, no direct evidence that the gradient of excitation by low tones changes in the manner required. For that reason we should give due consideration to other principles of explanation.

It may simply be that, for the low tones, the general form and extent of the pattern of excitation is enough to permit the discrimination of frequency without appeal to the principle of maximal stimulation, or to the principle of gradients. In other words, it is possible that we are sensitive to the gross location of a pattern, rather than to some specific feature of it.

Present evidence does not permit us to state definitely by what aspect of basilar excitation one tone is distinguished from another in pitch. Of this, however, we may be certain: the position of basilar disturbance is related to the perceived pitch of a tone. We have seen, furthermore, that there are open to us certain reasonable possibilities for explaining the high resolving power of the ear. Among these possibilities future experiments may decide.



FIG 145 A representation of the manner in which a change of gradient in the pattern of excitation due to low tones may give rise to perceptible saliences. Curve *A* would be for a lower frequency than curve *B*.

CHAPTER 16

AUDITORY NERVE-IMPULSES

FROM the point of view of the psychophysiology of auditory sensation, the auditory nerve stands in the position of a gateway between the sense organ and the brain. The afferent impulses which form the physiological basis for the whole range of auditory sensation must pass through this single 'bottle neck'. The nerve is not scattered anatomically, like the nerves of the cutaneous or the proprioceptive senses, and, theoretically, the entire primary sensory input can be assessed and measured at this point. Sound waves initiate movements in the structures of the inner ear which we can study and analyze by means of the aural microphonics, but it is only by way of the impulses in the auditory nerve that the sense-organ can affect the higher nervous centers and lead to the reactions which we call sensations. The impulses which pass up the auditory nerve must possess certain properties of number, distribution among the various fibers, temporal sequence, etc., which are the correlates of and the basis for the various psychological attributes of sound. Knowledge of the neural correlates of the discriminable aspects of sound has an additional general interest in that it may reveal what types of relations among nerve impulses are capable of central discrimination.

ANATOMICAL CONSIDERATIONS

The distribution of the terminal branches of the auditory nerve fibers to the hair cells and the arrangement of the cell bodies of the primary sensory neurons in the spiral ganglion of Corti have been described in Chapter 10. The axons of the ganglion cells are gathered together within the modiolus

to form the auditory portion of the eighth cranial nerve. At the point where this nerve passes through the petrous bone, it is associated with the vestibular portion of the eighth nerve which serves the sense-organs of the semicircular canals, the saccule, and the utricle. The entire nerve emerges through the internal auditory meatus. The intracranial course of the eighth nerve is short, not more than 4 or 5 mm in the cat, for the nerve immediately enters the medulla in the region of the *cochlear nucleus* and *tuberculum acusticum* (see Fig 112, p 270).

The fibers of the auditory nerve show a curious spiral arrangement. Those fibers which connect the cochlear nucleus with a region about one-quarter of the length of the basilar membrane from the round window run straight and constitute the axis of the nerve. Around these fibers the other fibers are twisted—those going to the apex, in one direction, those going to the basal region, in the opposite direction. Thus, the twisting corresponds to the coiling of the cochlea, and the nerve as a whole is twisted somewhat like a rope. The genesis of this arrangement may be readily understood from the embryological development of the cochlea, for the nerve fibers are dragged, so to speak, after the organ of Corti as it grows out into its final spiral form (Lorente de N6, 2, Poljak, 1).

Upon entering the medulla, each fiber of the cochlear nerve divides, as shown in Fig 146, into an ascending branch which goes to the *ganglion ventrale* and a descending branch which enters the *tuberculum acusticum*. The ascending and descending branches are arranged in parallel bundles. If the points of division of the primary entering fibers are projected on a longitudinal plane, they form a slightly curved line. This line is the caudal boundary of the *ganglion ventrale*, but what is more significant is that it represents a projection in the cochlear nucleus of the organ of Corti. There, if we imagine the ganglion of Corti to be uncoiled, the highest point in the line of bifurcations of the nerve fibers corresponds to the apical end of the ganglion and the lower end to the basal part of the ganglion. We shall see later (p 432) that a similar 'map' of the organ of Corti has been discovered in the medial geniculate

body This discovery is not surprising in view of the orderly arrangement of the fibers in the tract connecting the cochlear

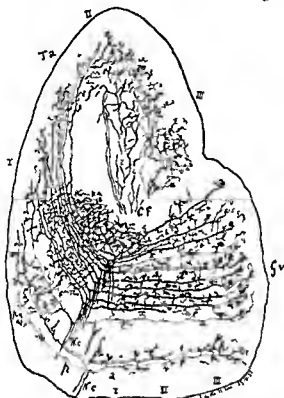


FIG. 146 Longitudinal section through the primary acoustic nuclei of a four-day-old cat prepared by the method of Golgi

Gv — ganglion ventrale of the cochlear nucleus

pn — posterior nucleus

Ta — tuberculum acusticum

I II and III indicate regions of specific structure within the tuberculum acusticum and the ganglion ventrale

Cf — centrifugal fibers from higher auditory nuclei

Nc.—fibers of the cochlear auditory nerve with anterior branches (a) for the ganglion ventrale and posterior branches (p) for the tuberculum acusticum and posterior nucleus The map of the bifurcations of these fibers represents a map or projection of the cochlea in the cochlear nucleus The fibers from the apex of the cochlear branch near the center of the figure and those from the central part of the cochlea near the bottom of the figure (Lorente de N6 2)

nucleus with the medial geniculate body An equally orderly arrangement of fibers in the auditory radiations which connect

the medial geniculate with the temporal cortex argues strongly for a third projection of the organ of Corti in the cerebral cortex

ELECTRICAL DETECTION OF IMPULSES IN THE AUDITORY NERVE

The action potentials of the auditory nerve may be recorded by means of appropriate electrodes placed in the auditory nerve or on the cochlea itself. Within the medulla the problem of recording becomes more complex, for the primary neurons of the auditory nerve stimulate secondary neurons in the cochlear nucleus and, within the nucleus, both primary and secondary impulses may be detected by the electrodes. Recording from the cochlea yields action potentials as well as aural microphonics, but the microphonics are the more powerful and can not be suppressed by any procedure which does not also abolish the nerve impulses. Only when we make the microphonic very brief, as in a faint click, so that the nerve impulses, by virtue of their longer latency, appear after the microphonic, can we record uncomplicated action potentials from the cochlea.

Ordinary wire or wick-electrodes applied directly to the auditory nerve detect not only the action potentials but also the aural microphonics, because the microphonics spread widely from the cochlea, particularly along moist surfaces such as the meninges of the brain. The microphonics may be excluded by employing coaxial electrodes, which are made by passing a fine insulated wire down the bore of a hypodermic needle. The wire is held in place by insulating cement, and ground off flush with the bevel of the needle. The wire serves as the 'active' electrode and is connected to the input grid of the amplifier, while the needle itself acts as the ground or 'reference' electrode, and also provides the necessary mechanical support. Electrodes of this type are very useful for electrical exploration within the substance of the brain, for they pierce the brain with relatively slight trauma. The radius within which electrical effects are picked up by coaxial electrodes is quite small, so that it is possible to determine with fair accuracy the location of the active nerve fibers responsible for the potentials. Moving the needle

a millimeter or less may reduce the electrical record of impulses in a particular tract to as little as one tenth of its former size.

CHARACTERISTICS OF SIMPLE AUDITORY ACTION POTENTIALS

The simplest auditory action potential would consist of a single nerve impulse in a single auditory fiber. This degree of simplification has been reasonably approximated by using as a stimulus a click whose strength is just above threshold. With this stimulus, very few fibers are simultaneously stimulated and only one impulse is initiated in each. Such a volley may be recorded either at the round window or in the auditory nerve (Fig 147).

Duration The duration of the action potential in a fiber of the auditory nerve is less than 1 msec. In both duration and wave form it resembles the action potentials of other modulated fibers of similar diameter.

Velocity of Conduction The time interval between the appearance of the action potential in the cat's cochlea and in the auditory nerve is about 0.15 msec. The distance from the basilar membrane to the usual position of the electrodes in the nerve is about 4 mm. The velocity of conduction is therefore about 30 meters per second. This is similar to the velocity of impulses in cutaneous sensory nerves and in the optic nerve. The figure is only approximate, because the length of fiber traversed is not accurately known, and also because it is assumed that the action potential is registered at the round window as the impulse crosses the basilar membrane and before it enters the bony structure of the modiolus. The assumption seems reasonable, however, in view of the good insulating properties of the petrous bone.

These measurements point clearly to the physiological similarity of the auditory nerve and other sensory nerves, and they render improbable any assumption that the fibers of the auditory nerve possess special properties which would provide them with an unusually brief refractory period.

Polarity The polarity of the action potentials from the

cochlea or from the auditory nerve is constant. For example, an electrode on the round window always records a large initial negative peak which may or may not be followed by secondary waves. The first *action potential* wave is always negative, whether the initial wave of the cochlear microphonic preceding it is negative or positive*. The electrical sign of the first *microphonic* wave depends upon whether the first sound wave is one of negative or of positive pressure (see p 318). When the sound is a click generated by discharging a condenser through a loud speaker, the direction of the initial pressure wave and the polarity of the initial microphonic wave may be reversed by reversing the electrical polarity of the condenser-discharge. The ensuing action potential, however, remains negative (Fig 147 B₁), just as the action potential in any other nerve remains negative regardless of the nature or polarity of the stimulus which initiates the impulse. This uniform polarity of the action potential provides a ready means for distinguishing the two components in the electrical pattern at the round window following an impulsive stimulus, and it attests the fundamental difference in the origins of the action potentials and the cochlear microphonics.

Latency The action potential produced by a click is not simultaneous with the first wave of the cochlear microphonic. The action potential recorded from the round window follows the microphonic by at least 0.55 msec, and sometimes by as much as 2.0 msec, depending upon the polarity and intensity of the stimulus. These relations and their implications will be considered later in detail.

Vulnerability In the event of death to the experimental animal, or the interruption of the oxygen supply to the cochlea, the action potentials disappear before the microphonics, although the microphonics fall to a fraction of their original

* The polarity and form of action potentials recorded by coaxial electrodes placed in the auditory nerve or brain depend upon the position of the electrodes relative to the active fibers. The form is rarely monophasic, sometimes diphasic and often triphasic. This complexity is due in part to the geometry of the electrodes and in part to the complex conducting and shunting effects of the surrounding tissue.

intensity at the death of the animal. The action-potentials in the higher auditory pathways, beyond the synapses of the cochlear nucleus, are even more vulnerable than those of the

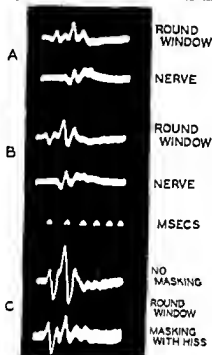


FIG 147 Standing wave oscillograms of the cochlear microphonics and action potentials in response to clicks, recorded from the round window and from the auditory nerve. The records from the nerve were obtained with coaxial electrodes and show action potentials without microphonics. The response consists of three, and perhaps four, fairly discrete waves. These same waves appear in the round window records, but there they are superimposed on the later waves of the cochlear microphonics.

In *B* the stimulus is the same as in *A* except that its polarity has been reversed. Note that the first wave of the cochlear microphonic is inverted in *B* but that the action potentials retain the same polarity in *B* as in *A*.

In *C* both records are from the round window. The first corresponds to *B* except that the stimulus is stronger. In the second a hissing sound is delivered to the cat's ear in addition to the clicks. The base line is broader, due to the microphonics and action potentials of the hiss which are not synchronized with the sweep of the oscillograph. The cochlear microphonics of the click are unaffected by the hiss, but the action potentials are greatly reduced or 'masked' (Derbyshire and Davis, 2).

auditory nerve, and they may be abolished by deep surgical anesthesia.

Threshold. The threshold intensity required to initiate an observable action potential depends upon two factors: the thresholds of the individual nerve-fibers, and the number of fibers which must be simultaneously excited in order to generate a detectable potential across the electrodes. The exact placement of the electrodes in relation to the active fibers is critical in determining whether or not the impulses from a few fibers will be detected. A fortunate placement makes it possible to detect simultaneous activity in a very few fibers, perhaps five or six, but there is as yet no clear evidence for the successful detection of impulses in a single auditory fiber. Since the nerve-impulses are all-or-none in character (see Chapter 12), the problem of their detection hinges upon the number of fibers stimulated and upon the placement of the electrodes, and not upon any increase in the size of the individual impulses.

With good placement of the electrodes in the auditory nerve, the threshold for action-potentials in response to clicks (or low tones) is within a few decibels of the threshold for the aural microphonics at the round window. This correspondence is convenient, but presumably fortuitous, and it has no theoretical significance, except as it justifies the practical use of the threshold for the microphonics as an experimental measure of the sensitivity of the ear. In some experiments the threshold for action potentials, in the higher auditory pathways of the cat, has been found to be actually lower than the threshold for the corresponding aural microphonics, and quite as low as the average threshold for human hearing (Kemp, Coppée, and Robinson). The microphonic threshold, it will be recalled, is defined as an arbitrary—just detectable—potential (see p. 313).

Relation to Sound-Intensity. The intensity of short impulsive stimuli affects both the amplitude and the latency of the resulting action potentials.

Amplitude. As the intensity of a click is increased, both the cochlear microphonic and the action-potential grow larger. Near threshold, the increases can be measured satisfactorily from the round window (see Fig. 148 A) but, at 30 or 40 db above threshold, measurement becomes difficult, because the mechanical response of the ear to a click is not critically damped.

(see p. 262) and the action-potentials are superimposed on the later waves of the microphonics. The degree of complexity which this introduces depends in part on the sharpness of the click and the shape of the resulting microphonic pattern. Precise measurements are therefore impossible at high sound-intensities, but it can be seen that the action-potential continues

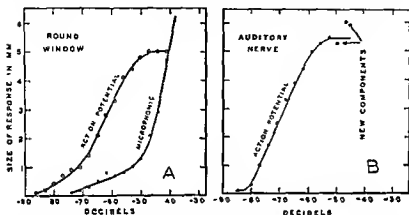


FIG 148 The amplitude of the first wave of the action potential as a function of the intensity of a stimulating click.

A Recorded from the round window of a cat. The growth of the action potential differs strikingly from the growth of the cochlear microphonic.

B Recorded by coaxial electrodes from the auditory nerve of the same animal. This curve differs from both of the curves in *A*. The latency of the action potential of the nerve was 1 msec longer than that of the first action-potential wave at the round window. The unusually long difference in latency and the different shapes of the amplitude curves show that the action potentials of *A* and *B* probably do not belong to the same nerve-fibers. This fact illustrates the difficulty in drawing conclusions from measurements of a random sample of neural activity detected by coaxial electrodes. (After Derbyshire and Davis, 2)

to increase, as well as the cochlear microphonic, although they do not necessarily follow the same law of increase.

Growth in the size of the action-potential implies increase in the number of fibers stimulated, but it is entirely uncertain how linearly the size of the action-potential registers this numerical increase, for all fibers are not located in equally advantageous positions with respect to the recording electrodes. This difficulty is particularly serious when coaxial electrodes are

inserted into the auditory nerve or higher tracts (see p. 422). Therefore, the law of growth of the action-potentials remains uncertain, and we cannot make significant quantitative comparison between it and psychological data. Furthermore, as will appear below, the action-potentials in response to a click do not represent a single synchronized volley of impulses but a series of volleys of various latencies, originating at various positions along the basilar membrane. The data of Fig. 148 are based on the measurement of only one, the earliest, of these volleys.

Latency. The latency of the nerve-impulses diminishes with increase of intensity of the stimulating click. This change

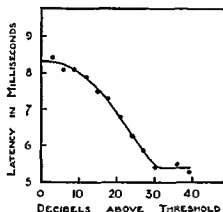


FIG 149 Latency of the first wave of the action potential at the round window in relation to the intensity of the stimulating click. The latency was measured from the first major negative peak of the cochlear microphonic to the foot of the first wave of the action potential. The latency diminished by 0.29 msec as the intensity was increased to 30 db, but at greater intensity it remained constant. The first half-cycle of the cochlear microphonic occupied 0.26 msec (Derbyshire and Davis, 2)

can be accurately measured for the first volley of impulses and it appears to characterize the later volleys as well. In the particular case illustrated in Fig. 149 the latency diminished from 0.84 msec to 0.53 msec as the stimulus was increased from threshold to a level of 30 db above threshold. Further increase in intensity apparently does not further diminish the latency of the nerve-impulses.

THE RESPONSE TO STRONG IMPULSIVE STIMULI

The action potential wave in response to a single click is not simple except near threshold. When the intensity of the stimulus is increased by a few decibels, additional action potential waves appear in the auditory nerve, giving the composite wave illustrated in Figs 147 and 150. The group is usually composed of three major waves which differ in latency, maximal amplitude, and threshold. These waves merge more or less into one another. The pattern differs in detail, according to the frequency spectrum of the click, but the impulses are considerably dispersed in time, except when a stimulus very near threshold is employed. The earliest wave is sharp and prominent when the click is generated by passing a condenser-discharge through a loud speaker designed for high tones (3000 to 10,000 cycles). The early wave is less prominent when a loud speaker designed for a lower range (60 to 4000 cycles) is used. This difference in pattern of the neural response is presumably due to contributions from different parts of the organ of Corti and constitutes the basis of the ability of the human ear to distinguish the clicks from one another by their tonal quality, even at an intensity so low that no nerve fiber carries more than one impulse in response to each click (cf Fig 117, p 283).

The three waves shown in Figs 147 and 150 have been arbitrarily designated *F*, *G*, and *H* in order of increasing latency. The figures for latency given on page 385 refer entirely to the earliest, *F*, wave. The latencies of the later waves can be measured only to the peak, since the foot of each overlaps the previous wave. Representative figures for the latencies measured from the first negative peak of the aural microphonic to the peaks of the three waves recorded from the round window are *F*, 0.7 to 1.0 msec, *G*, 1.9 msec, and *H*, 2.6 msec. The latencies of *G* and *H* shorten like that of *F*, and to the same degree, with increase of the intensity of the stimulus.

The threshold for *G* and *H* is usually about 10 db below that for the aural microphonic when the 'high frequency' speaker is the source of the click, and when the potential is recorded from the round window. The *F* wave and the coch

lear microphonic first appear at about the same intensity of stimulation. The *F*, *G*, and *H* waves all reach their maximal amplitudes at 30 to 40 db above their respective thresholds, although with further increase in intensity the cochlear microphonic continues to increase.

Somewhat similar waves are seen in the action-potential

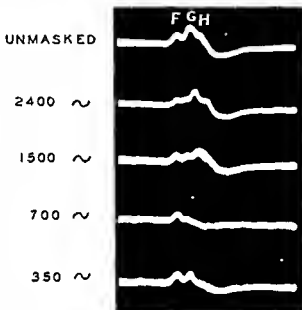


FIG 150 Standing wave oscillograms of action potentials in response to clicks, recorded from the lateral lemniscus of a cat. These oscillograms show preferential masking of different components by tones of different frequencies. High tones reduce the earlier and low tones the later components. The *F*, *G*, and *H* waves are indicated in the unmasked record. (The swing below the baseline after the *H* wave is an artefact introduced by the small coupling condensers which were employed in order to stabilize the amplifier for clear photography of the standing waves.) (After Kemp, Coppée, and Robinson.)

records obtained from mixed peripheral nerves which have been stimulated electrically (Erlanger and Gasser). The waves in peripheral nerves are due to differences in the velocity of conduction in different groups of nerve-fibers. The slower impulses lag behind the faster ones and appear as later waves in the composite action-potential. The differences in velocity are correlated with differences in the diameters of the nerve-fibers. Large

fibers conduct impulses more rapidly, small fibers more slowly. The fibers of the auditory nerve, however, are quite uniform in diameter about 5 microns (Lornte de No, 2). We should therefore expect uniform velocities of conduction, and, consequently, we must seek another explanation for the occurrence of separate waves in the click response in the auditory nerve.

The *F*, *G*, and *H* waves apparently represent volleys of impulses in different groups of fibers in the auditory nerve fibers which innervate different portions of the basilar membrane. The evidence for this statement depends upon the suppression or 'masking' of one or another of the waves when tones of various frequencies are sounded at the same time as the clicks. The phenomenon of masking will be considered in the next chapter, but for the present we may interpret the fact of such interaction between a particular tone and a click as evidence that both stimuli are activating the same portion of the basilar membrane.

The earliest (*F*) wave is preferentially masked by high tones, and the latest (*H*) wave by low tones. In a typical case illustrated by Fig. 150 the *F* wave was selectively masked by a tone of 2400 cycles. A tone of 1500 cycles caused greatest depression of the middle (*G*) portion of the response, while 350 cycles was particularly effective in masking the late (*H*) portion. Complete masking of any wave is difficult to attain with a pure tone, since the click response will mask the tonal wave itself if it falls in the proper phase of the tone (see p. 409). With strong masking tones of any frequency all waves are somewhat reduced, but the superior effectiveness of certain frequencies is very clear. Since the *F* wave is selectively masked by a tone of 2400 cycles, we may infer that it is composed of nerve impulses traveling in the nerve fibers which arise in the portion of the basilar membrane which is tuned to 2400 cycles. This portion of the membrane must, therefore, be stimulated by the click before the portion tuned to the lower frequencies which give rise to the *G* and *H* waves. We have already seen, in Chapter 10, how this temporal dispersion of the nerve impulses in response to a click supports the concept of traveling waves on the basilar membrane.

THE STIMULATING PHASE OF THE COCHLEAR MICROPHONIC

The latency of the first volley of nerve impulses, measured from the start of the cochlear microphonic, varies with the *polarity* of the sound waves. For a given intensity, however, the latency of the first action potential is constant when measured from the *negative peak of the large initial cycle* of the cochlear microphonic (see Table V). We may conclude, therefore, that the nerve impulses are initiated during only one phase of the cochlear microphonic, the one in which the round window is passing from electrical negativity to electrical positivity. This particular phase of the microphonic is associated with

TABLE V

Polarity of first large wave of the cochlear microphonic	Latency of F wave of action potential measured from	
	Negative peak of microphonic	Positive peak of microphonic
Positive	0.70 msec	1.02 msec
Negative	0.70 msec	0.55 msec

outward movement of the stapes and the tympanic membrane (cf Fig 133, p. 342). If the first major electrical change at the round window is from positive to negative, no impulses are set up during this phase. They are delayed until the negative-to-positive phase of the cochlear microphonic ensues. It is significant that, in the cases so far studied, the decrease in latency with increase of intensity is quantitatively nearly equal to the duration of this negative-to-positive phase of the first major wave of the cochlear microphonic. We may suppose that at threshold the necessary condition for stimulation is achieved only near the end of the negative-to-positive phase, but with great sound intensity it occurs very near the beginning.

THE MECHANISM OF STIMULATION OF THE
AUDITORY NERVE

The association of nerve stimulation with a particular phase of the cochlear microphonic does not imply that the electric potential itself stimulates the nerve, although this hypothesis has been proposed. The hypothesis of electrical stimulation of the nerve is attractive for its simplicity, but it encounters one serious objection. It does not adequately explain the long latency of 0.6 msec or more, exhibited by the auditory nerve impulses. The shortest latency of the nerve impulses which has been measured, even with maximal stimulation, is 0.53 msec (Derbyshire and Davis, 1, 2). On the hypothesis of electrical stimulation, the latency must be explained by (a) utilization time of the stimulus acting on the nerve fibers and (b) slow conduction in the nonmedullated terminal twigs of the nerve fibers. But, if the properties of the auditory nerve fibers are similar to those of other nerves, the utilization time for maximal stimuli should be not more than 0.1 msec at the most. If we ascribe 0.1 msec of the delay to utilization time and the remainder to conduction time, we must assume a rate of conduction of less than 10 cm per second for the nonmedullated terminal twigs, because the velocity in the medullated portion is about 30 meters per second and the length of the shortest nonmedullated twigs from the internal hair-cells to the beginning of medullation is only 30 microns (Lorente de Nó, 2). Such unusually slow conduction is a very difficult assumption to accept, particularly when we realize that the refractory period of the terminal twigs is as brief as that of large medullated fibers themselves (see p. 401).

Another difficulty with the hypothesis of electrical stimulation lies in the effectiveness with which the higher audible frequencies can stimulate the nerve fibers. Other nerve fibers stimulated by alternating currents of 1000 cycles or more show a very high threshold, and the threshold rapidly rises with continued stimulation. Auditory fatigue, whether measured subjectively (p. 217) or by action potentials (p. 397), does not vary with frequency to anything like the extent demanded by a simple theory of electrical stimulation.

A more promising hypothesis is that stimulation of the nerve fibers results from the formation or liberation of a chemical mediator (Derbyshire and Davis, 1), as a direct result of the mechanical deformation of the hair cells. The most obvious advantage of this hypothesis is that the latency of the nerve-impulses is easily explained by the theory of chemical mediation. The latency represents the time required for diffusion of a chemical substance to its point of action upon the nerve fibers and for the subsequent stimulation of these fibers. No suggestion as to the nature of the hypothetical mediator has been offered, but the hypothesis is intended to be analogous to the theory of chemical mediation now generally accepted for neuromuscular, for neuroglandular, and for certain instances of synaptic transmission (Cannon and Rosenblueth).

Chemical transmission or mediation of nervous effects was originally demonstrated by the following experiment by Loewi. Two isolated frog hearts, beating spontaneously, were arranged so that the fluid which perfused the first was collected and used to perfuse the second also. The vagus nerve to the first heart was stimulated. The contractions of the first heart became weaker and its rhythm slower, which is the usual effect of nerve impulses reaching a heart by way of the vagus nerve. But the rhythm of the second heart was also slowed, and the contractions were weakened. No nerve impulses reached the second heart, but effects corresponding to vagal nerve impulses were transmitted to it from the first heart by way of the perfusing fluid.

A chemical substance or 'mediator' is liberated at the terminations of many nerve fibers when impulses reach them. For the vagus nerve, the mediator has been identified as *acetylcholine*, an unstable ester of choline. Acetylcholine is liberated at all the nerve terminations belonging to the cranial and sacral divisions of the autonomic nervous system. It is also liberated by the motor fibers which innervate skeletal muscles. Acetylcholine also mediates the transmission of activity from one neuron to another across the synaptic junctions of the superior cervical ganglion, and probably across many other synapses in the nervous system. When acetylcholine is injected

into the blood stream, it is hydrolyzed with great rapidity by an enzyme which is normally present in the blood and tissues. This very rapid destruction prevents the acetylcholine liberated by a nerve fiber from exerting its effects in other organs than the one in which it is liberated—a fortunate provision indeed.

Acetylcholine is not the only chemical mediator of nervous effects. At the terminations of the fibers of the sympathetic division of the autonomic nervous system, in the heart, in the muscular walls of the blood vessels, in the intestine, and in many other organs, the mediator is *sympathin*. The chemical structure of sympathin has not been established, but it is known to be closely allied to adrenin, the hormone secreted by the medulla of the adrenal glands. In fact, adrenin itself may properly be regarded as a chemical mediator of nervous effects whose action is much more diffuse and persistent than that of acetylcholine. Several other mediators exist and control various functions such as the activity of chromatophores in fish and amphibia (Parker).

The existence of not only one but of several chemical mediators is firmly established. Chemical mediation is so widespread, indeed, that we may well suppose it is the general mechanism by which activity in one cell initiates activity in another cell, just as the electrochemical mechanism of nerve-conduction, outlined in Chapter 11, is the general type of all-or none conduction within single nerve cells. If chemical mediation is the fundamental principle of intercellular transmission, then it is quite reasonable to suppose that sensory cells, such as the hair cells of the organ of Corti, should stimulate the sensory nerve fibers by means of a chemical mediator. The mediator may or may not be acetylcholine, but it is worth noting that the very rapid destruction of acetylcholine by its esterase (Marnay and Nachmansohn) would make it possible for the substance to appear and disappear with the flash like rapidity needed to generate nerve impulses at frequencies up to 1000 per second.

CHAPTER 17

NERVE IMPULSES IN RESPONSE TO TONAL STIMULATION

IN THE previous chapter we have considered the fundamental properties and relations of nerve impulses in the auditory nerve. These properties are most clearly revealed by the relatively simple volleys of impulses initiated by single clicks. We have seen that the impulses are in all respects similar to the impulses in other sensory nerves. The all-or none impulse is the physiological unit of nervous activity, and the response of the auditory nerve to tonal stimulation must consist of a series of such impulses.

SYNCHRONIZED ACTION POTENTIALS

From the point of view of the auditory nerve, a tonal stimulus consists of a series of discrete stimuli. Each sound wave is itself a separate stimulus. Therefore, the general laws governing the stimulation of nerve fibers by repetitive stimuli have here an immediate application. Particularly important is the limitation set by the refractory phase upon the frequency at which a fiber may be made to respond to repeated stimulation. It is a necessary consequence of the all or none law that the impulses in a single nerve fiber are unable to keep pace with the frequency of a sound when the frequency exceeds a certain value. *At frequencies above the critical value the total response of a nerve containing many fibers may still appear to follow the frequency of the stimulus, but under these conditions each individual fiber does not respond to every sound wave, but only to every second, third, or fourth wave, according as its refractory period may determine (see p 401).* The nerve impulses group themselves in relation to the sound waves, because of the fact that the impulses are set up in a definite phase of the cochlear

microphonic and hence in a definite phase relation with the stimulating tone

In response to tones below 400 cycles, the response of the auditory nerve is a series of volleys of nerve-impulses, and the impulses in each volley are so nearly simultaneous that they are clearly separated from one another by a temporal interval, as shown by the straight oscillographic baseline in Fig. 151. The impulses in each volley are, however, slightly dispersed in time, just as we should expect from our knowledge of the mode of vibration of the basilar membrane (cf. Fig. 118, p. 285). The temporal dispersion serves to give the composite waves a

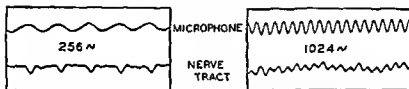


FIG 151 Oscillograms of action potentials in response to steady tones, compared with the response of a microphone to the same tones. The action-potentials from the lateral lemniscus of the cat in response to a 256-cycle tone are a series of (downward) 'spikes' separated by nearly flat baseline. At 1024 cycles the spikes merge into a nearly sinusoidal wave (After Hallpike, Hartridge, and Rawdon-Smith. By permission of The Royal Society of London.)

slightly broader and more rounded contour than that of single action-potentials. As the frequency of the stimulating tone is increased, the volleys occur closer and closer to one another; and, when the interval between the volleys is finally reduced to zero and the volleys begin to overlap, the total pattern becomes more and more sinusoidal (Fig. 151).

The action-potentials of the auditory nerve may follow the frequency of the stimulating tone up to approximately 3000 cycles. The reproduction by the action potentials of the frequency of the stimulating tone constitutes the original 'Wever-Bray effect,' although this term is now more often applied to the aural microphonics or to an indiscriminate mixture of microphonics and action potentials. It was probably an unsuspected admixture of aural microphonics in the original experi-

ments which led Wever and Bray to place the frequency-limits for "auditory nerve-impulses" as high as 4100 cycles. When coaxial electrodes are employed to shield against the aural microphonics, the upper limit of frequency for synchronized action-potentials of the cat may be as high as 4000 cycles; but nearly maximal stimulation is required to obtain a synchronized response between 3000 and 4000 cycles, and the response may rapidly lose its synchronized character with continued stimulation.

Relation to Intensity. The size of the recorded action-potentials of the auditory nerve increases to a definite maximum with

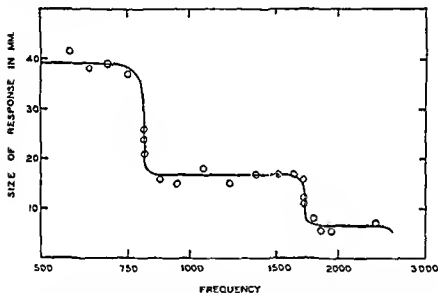


FIG 152 The initial size of the action potential in the auditory nerve of a cat as a function of frequency. The sudden drops in the curve are due to the fact that above a critical frequency (800 cycles in this experiment) the individual fibers cannot follow the frequency of the stimulus, but must alternately respond to every other vibration. At twice this critical frequency each fiber responds only to every third vibration. (Stevens and Davis.)

the intensity of the stimulating tone. This maximum, beyond which no further increase can be observed, recalls the similar maximum exhibited by the aural microphonics, and it is reached at approximately the same intensity of stimulation. The maximal response is approximately constant for all frequencies in

the range below 900 cycles, although the presence of higher harmonics makes accurate measurements difficult for tones below 400 cycles

Maximal Amplitude as a Function of Frequency Figure 152 shows the relation of the maximal amplitude of the action potentials to frequency. As the frequency is increased, a critical value is reached, usually at about 900 cycles, at which the maximal amplitude falls more or less abruptly to a little less than half its previous value. It remains at this level until a second critical frequency, equal to twice the first, is reached. A new level is then established at less than one third the original amplitude. At three times the first critical value, 2700 cycles in this instance, there is another fall in amplitude. The ampli-

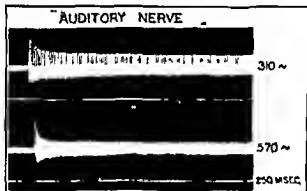


FIG 153 The onset of a 310-cycle tone produces an on-effect in the auditory nerve followed by synchronized action potentials which show moderate equilibration. The 570-cycle tone produces an on-effect followed by synchronized action potentials which show marked equilibration. It is unusual to find so much equilibration at a frequency as low as 570 cycles. (After Derbyshire and Davis 2)

tude here is too small for accurate measurement, although the waves may still be seen on a cathode ray oscillograph. Between 3500 and 4000 cycles the synchronized response is lost entirely. Impulses ascend the nerve when a high tone stimulates the ear, but the impulses are not synchronized with one another, or with the stimulating tone. The discharge is then random, or *asynchronous*, like that in a cutaneous sensory nerve when many

sense-organs are stimulated by a stroking of the skin. This type of discharge appears on an oscillograph as a roughened baseline. In a loud-speaker the response is a rustle, or low hiss, of rather characteristic quality, and, although its measurement is difficult, it may be used for determination of thresholds.

FATIGUE AND EQUILIBRATION

The foregoing description of the behavior of action-potentials at various frequencies is based on measurements made immediately after the on-effect of the action-potentials evoked by a tone 70 db above threshold. The on-effect of the action-potentials

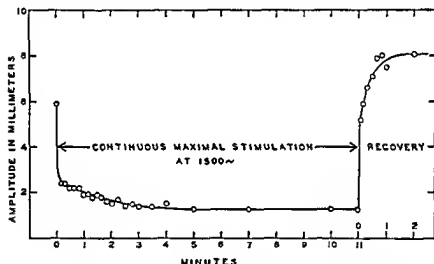


FIG 154. The amplitude of the action potential of the auditory nerve during and after continuous stimulation at 1500 cycles, showing slow equilibration and recovery. The initial phase of fast equilibration (see Fig 153) occurred too rapidly to be plotted on this time scale. During recovery the stimulating tone was sounded for about half a second every five seconds and the initial size of the action potentials recorded. (Derbyshire)

consists of a large initial volley of nerve-impulses. Following the on-effect the action-potentials do not remain constant in size, as do the aural micropbonics, but shrink, first rapidly and then more slowly, to a lower amplitude (Fig. 153). The rate and extent of this shrinkage are definite functions of the frequency of stimulation (cf. p. 301). The reduction in the initial

size of the potential presumably represents a readjustment of the chemical dynamics in the nerve fiber and the attainment of a new equilibrium between anabolism and catabolism. For this reason the readjustment has been termed *equilibration*. It is a special case of fatigue, in that it represents an adjustment to a new level of sustained activity and not an exhaustion of reserve material. Recovery is complete within 30 sec after the end of a period of stimulation during which equilibration has occurred.

Equilibration is not to be confused with the hysteresis of the cochlear microphonics (see p. 326), for equilibration occurs with submaximal as well as with supramaximal stimulation, and is a function of the *frequency* but not of the *intensity*, of stimulation. The shrinkage continues as shown in Fig. 154, for 5 to 7 min after the onset of a stimulating tone, although it is much greater and more rapid during the first 2 sec than during any later period. An arbitrary measure of the degree of equilibration may conveniently be made after 2 sec, in which event, the initial value, with respect to which the equilibration is measured, should be determined immediately after the on effect has subsided.

MAXIMAL FREQUENCY OF IMPULSES IN EACH FIBER

The general principle is well established that the degree and the rate of equilibration of nerve impulses are greater, the higher the frequency of impulses in a nerve fiber. This fact enables us to determine with assurance the maximal frequency of impulses in the individual fibers of the auditory nerve by determining the degree of equilibration as a function of the frequency of the stimulus. Below 400 cycles, equilibration is slight. It becomes greater when the frequency is increased and it reaches a maximum (where the shrinkage is greatest) at 900 to 1000 cycles. It is upon passing through this same frequency range of 900 to 1000 cycles that the size of the initial response falls sharply to about one half of its former value. The equilibration passes through a second maximum a little below 2000 cycles where the initial response falls to its third

plateau Another maximum in equilibration can usually be seen to occur near 3000 cycles, but the size of the synchronized action potential is here so small that satisfactory measurements are impossible

The appearance of maxima of equilibration at three different frequencies, one of which is double and another treble the lowest, identifies the lowest of the three (about 900 cycles) as the maximal frequency of impulses in each fiber This maximal frequency is imposed by the refractory period of the nerve fibers Above 900 cycles each fiber responds only to alternate sound waves, so that when the frequency of the tone is 1400 cycles each nerve fiber is presumably carrying 700 impulses per second This behavior of the nerve fibers is termed *alternation* Above the second critical frequency of 1800 cycles, each fiber responds to only one sound wave in three, and the behavior can then be described as *rotation* The reduction of the initial response (after the on-effect) to approximately one half and then to approximately one third of its original size is easily understood on the basis of alternation and rotation, for, when each fiber responds only to alternate sound waves, the total number of fibers active at any one time is only half as great as when each fiber responds to every wave

The phenomenon of alternation is not confined to the mammalian auditory nerve Alternation, rotation, and equilibration have all been demonstrated in the eereal nerve of the cricket (Pumphrey and Rawdon Smith) In this nerve the critical frequency is about 400 cycles instead of 900 cycles

When we make actual measurements on a cathode ray oscillograph of maximal amplitude and of equilibration as functions of frequency, we do not always encounter abrupt changes at the critical frequencies, although some change is usually evident The critical points become less and less definite as the experimental preparation ages After periods of exposure by operation, under anesthesia, the individual fibers tend to exhibit lower critical frequencies, and the total picture becomes increasingly blurred Under ideal conditions, however, we may observe effects which approximate those pictured schematically

in Fig. 155. These curves are those which, theoretically, should be obtained from an ideally fresh and uniform nerve. The upper curve represents the maximal amplitude of the observed action-potential. It falls abruptly from 12 units to 6 at 1000 cycles. At 2000 cycles it falls to 4 units, and at 3000 cycles to 3 units. The lower curve represents the percentage of the initial voltage of the action-potential which remains after 2 sec of

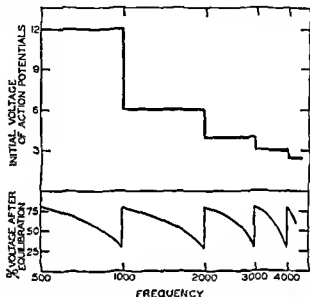


FIG 155 Schematic diagram showing the initial voltage of action potentials and the course of equilibration in an ideal nerve in which the refractory period of all the fibers is 1 msec (See text for explanation)

equilibration. It starts with a value of 80 per cent at 500 cycles and falls more and more rapidly until it reaches 30 per cent at 1000 cycles. It then rises abruptly to 80 per cent, which is the value it had at 500 cycles. The voltage remaining after equilibration falls again to 30 per cent at 2000 cycles, and then rises abruptly once more to 80 per cent. This sequence is repeated at the higher critical frequencies.

The simultaneous decrease, at 1000 cycles, in equilibration and in the amplitude of the total action-potential indicates that, in each fiber, the frequency of impulses has fallen to 500 per

second, or to one half that of the stimulating tone. Each fiber then responds only to alternate sound waves. At the higher critical frequencies the fibers resort to rotation, and then only a fraction of the total number of responding fibers is activated by any single sound wave. Under these conditions, we measure an action potential which is only a fraction of the size it would exhibit in response to a low tone. It should be noted that the fractional reduction in the observed action potential will equal the fractional reduction in the number of active fibers only when there is a direct proportionality between the number of active fibers and the potential generated between the electrodes. In actual experimental situations, this relation is probably never one of exact proportionality, although it may sometimes approach proportionality rather closely.

THE REFRACTORY PERIOD OF THE AUDITORY NERVE

The physiological process which sets an upper limit to the frequency of impulses in each fiber is the *refractory period* (cf p 301). For a brief interval of approximately 1 msec after each impulse the nerve fiber is not excitable and cannot transmit another impulse. One msec, corresponding to a maximal frequency of 1000 impulses per second, may be taken as the lowest value for the refractory period of an unfatigued fiber of the auditory nerve in an intact cat, and probably in man as well. Under most experimental conditions, however, the refractory period appears slightly longer than 1 msec.

It is evident that, within about 1 msec, functional recovery is sufficient for conduction in all parts of the pathway between the hair-cell and the cochlear nucleus. Even the fine non-medullated terminal twigs in the organ of Corti must recover at least as rapidly as this. The refractory period of a tissue, determined, as in the present case, by stimulation through natural physiological channels, we term the *functional refractory period*.

The functional refractory period of the auditory nerve is not always constant. It increases significantly as stimulation

is continued, and the threshold of stimulation for each fiber tends also to rise. In the higher nervous pathways, we find that the functional refractory period is approximately 1 msec throughout both the cochlear nucleus and the lateral lemniscus up to the inferior colliculus (cf Chapter 18). Above this anatomical level it apparently becomes much longer, or else differences in conduction time along different pathways become very great, for no synchronized impulses at frequencies above 100 per second have been detected from the auditory cortex or auditory radiations.

SCHEMA FOR THE AUDITORY NERVE

Knowing the significant properties of the individual fibers of the auditory nerve and the manner in which they are innervated, we may construct a schematic representation of their activity under stimulation by a pure tone. Such a representation should account for the phenomena which we observe by means of electrical recording: equilibration, synchronization, alternation, and rotation.

Figure 156 (Derbyshire and Davis) illustrates graphically how various factors combine to cause a high degree of equilibration near the critical frequency. In this diagram one fiber is assumed to have a functional refractory period less than 11 msec, to continue to respond with one impulse to each sound wave, and to show a moderate reduction in the size of each impulse. The next two fibers alternate when their functional refractory periods become prolonged beyond 11 msec. The fourth fiber is assumed to cease responding entirely after a short time. The net result is a very considerable shrinkage in the composite action potential.

This diagram demonstrates how the frequency of the stimulating tone is reproduced in the auditory nerve, even when the frequency is so high that no single fiber can respond to every sound wave. The principle of alternation and rotation allows for such reproduction up to the point at which temporal dispersion of the impulses in different fibers obscures the initial synchronization with the stimulating sound waves. The prin

ciple of rotation, essentially in its present form, was proposed as a theoretical possibility by Troland, prior to its experimental discovery by Wever and Bray (3) Troland employed the principle as a basis for his theory that "pitch is determined by

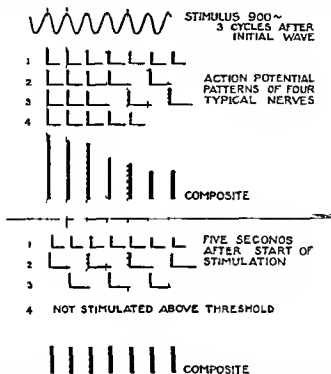


FIG 156 Schema of the response of four typical fibers of the auditory nerve showing how the development of alternation leads to fast equilibration and how the frequency of the stimulating sound may be reproduced by the action potentials even when no fiber can respond to every sound wave. The solid vertical lines represent the action potentials of individual fibers, which diminish slightly in amplitude with repetitive stimulation. The horizontal lines represent the duration of the functional refractory periods which become slightly prolonged during repetitive activity. The heavy vertical lines show the composite effect of the individual action potentials. The shortening of these lines represents a diminution in amplitude of the total action potential and the thickening represents a slight temporal dispersion of the individual impulses. (Derbyshire and Davis 2)

the frequency of a series of regularly spaced impulses, carried in a group of cooperating fibers' Wever and Bray called the principle the *volley theory*, and used it in developing a hypoth

esis of pitch perception similar to Troland's. The term 'volley theory,' however, used to designate a rotational activity set up by a rapidly intermittent stimulus is not entirely appropriate. 'Volley' implies that all units fire at once. In fact, for many years, this word has been used by Sherrington to designate a group of impulses initiated simultaneously in all the fibers of a nerve. The impulses in the auditory nerve might be thought of as a series of incomplete volleys, but a more apt military analogy to the rotational response by different groups of fibers would be 'platoon fire.'

THE THRESHOLD OF NEURAL ACTIVITY UNDER TONAL STIMULATION

It has already been pointed out that the threshold of nerve impulses for impulsive stimuli is very close to that for detection of the aural microphonics, and also to the threshold of hearing. The same generalizations apply to the neural response to tonal stimulation, provided the electrodes are properly placed in the auditory nerve. The correspondence is better for low tones than it is for the high tones which cause alternate or asynchronous response.

The threshold for a given tone is lower with the electrodes in one part of the auditory nerve than in another, and the position of the electrodes, in the nerve, which gives maximal sensitivity to a high tone is not the same as for maximal sensitivity to a low tone. This fact provides strong support for the place theory of the reception of tones of different frequency, but it has not proved possible to map the auditory nerve systematically with respect to the specificity of its fibers for different tones. This failure is presumably due to the complicated arrangement within the nerve of the fibers from different portions of the basilar membrane (see p. 377). In any event, it is clear that the threshold values are so much a function of the exact position of the electrodes that it is misleading to attempt the construction of a complete threshold-curve from any single experiment. Nevertheless, it is possible to state that the lowest thresholds found with the best placements of the electrodes correspond,

within a few decibels, to the thresholds of the corresponding aural microphonics.

RELATION TO INTENSITY OF TONAL STIMULATION

The voltage of the action-potentials recorded from the auditory nerve increases as the intensity of the stimulating tone is increased. Measurements of this voltage as a function of intensity are complicated by the phenomena of alternation and equilibration, but, at frequencies below 500 cycles, the curve may

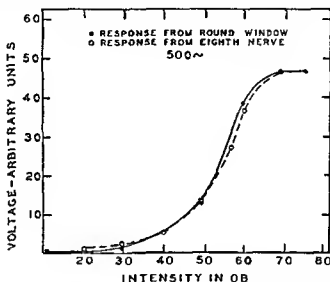


FIG 157 The initial voltage of the action potentials of the auditory nerve (broken line) and the voltage of the corresponding cochlear microphonics (solid line) as functions of the intensity of a 500-cycle tone. The voltage-scales are arbitrary and have been adjusted so that the two curves coincide at their maxima. The two amplitude functions run a very similar course in this case, but in many experiments they diverge significantly (Derbyshire and Davis, 2.)

correspond quite closely to the curve for the growth of the aural microphonics (Fig. 157). At other frequencies, such as 1000 cycles, the curve may depart rather widely from that of the microphonics. One reason for this is that near the critical frequencies alternation sometimes occurs with weak stimulation but not with strong. At frequencies above 3000 cycles,

where the nerve response appears essentially asynchronous, no significant measurements of neural activity have been made. As the intensity is increased, however, there is an obvious increase in the number of nerve impulses passing up the nerve per unit of time.

The maximal amplitude of the action potential, and the intensity of stimulation at which the maximum is reached, both depend rather definitely upon the exact position of the coaxial recording electrodes. Electrodes of this type are not equally affected by all the fibers in the nerve. Their sensitivity is limited essentially to those fibers in their immediate neighborhood. Therefore, we cannot assume that the recorded potential is a function only of the number of synchronously active fibers in the nerve, for it is also a function of their position relative to the electrodes. Other types of electrodes may be less limited in their ability to detect the activity of distant fibers, but, unfortunately, it is only with coaxial electrodes that it has been possible to eliminate the aural microphonics, and, if the microphonics are not excluded, measurement of the action potentials becomes quite impossible.

We should like, of course, to be able to measure the number of active nerve fibers as a function of intensity of stimulation. The nerve impulses are all-or none in character, and at low frequencies their frequency is determined by that of the sound waves. Therefore, increase in the voltage of the action potential must depend upon increase in the number of active fibers, and, as long as the impulses are synchronized with a stimulating sound wave, it is *only* by increase in the *number of active fibers* that there can be an increase of activity in the auditory nerve. At present we can say that, under the most favorable experimental conditions, the number seems to be approximately proportional to the magnitude of the aural microphonics. It is to be hoped that future experiments, with improved technique, will allow a more precise definition of this relation. There is probably no theoretical necessity for an exact proportionality.

The consideration that, when the frequency of the nerve impulses is determined by the frequency of the sound waves,

it is only by increase in number of active fibers that there can be an increase of activity in the auditory nerve points to the number of active fibers as the physiological basis for the attribute of loudness. This statement implies that change in loudness is associated with a corresponding change in the number of active fibers. It does not necessarily imply, however, that loudness is directly proportional to the number of active fibers. Summation of the central effects of single fibers may not occur in a simple arithmetical fashion, and, also, different fibers may form different central connections, so that some fibers may thereby contribute more than others to the total central nervous activity. Therefore we await more extensive experimental data in order to decide whether or not a simple numerical relation exists between loudness and the number of active fibers in the auditory nerve. (Cf p 151)

THE SUMMATION OF ACTION POTENTIALS

Since we find it expedient to regard the magnitude of the action potential as an experimental measure of the number of active fibers in a nerve, it is appropriate that we inquire more fully into the summation of the potentials from separate fibers. When nerve impulses pass simultaneously down two neighboring fibers in any nerve, the combined action potential is greater than when only one fiber carries an impulse. The combined action potential is approximately equal to the sum of the potentials recorded separately from impulses in the two fibers. It might appear at first glance, since the two fibers lie parallel to one another in the nerve, that the potential developed by impulses in two similar fibers should be no greater than the potential due to either one alone, as is true when two ordinary electric batteries are connected in parallel. Experimentally the potentials are additive, as if the batteries were connected in series. Two considerations make this apparent contradiction of an atomical fact seem reasonable. First, the potential of each nerve fiber is shunted by all the surrounding tissue, including neighboring nerve fibers. The more effective the shunting the less will be the potential recorded by a pair of electrodes placed

in contact with the nerve as a whole. When a second nerve fiber is active it also develops a potential and no longer acts as a mere passive electrical conductor shunting the potential of the first nerve fiber. This successive removal of shunts as more and more fibers become active is particularly important in a small nerve dissected free of surrounding tissue and laid upon a pair of electrodes.

The second consideration is more helpful for understanding the situation in a nerve, like the auditory nerve, which is buried in a large mass of surrounding tissue, so that the fraction of the total shunting effect which is contributed by each individual nerve fiber is very small. The nerve may be regarded as a group of tiny batteries, each of high internal resistance and all connected in parallel and shunted by the relatively low resistance of the surrounding tissues. Activation of two fibers instead of one reduces to one half the internal resistance of the source and nearly doubles the current flow in the external circuit. Therefore the potential detected by the recording electrodes between two points in the external circuit is practically doubled. The potentials of the individual fibers will add linearly, provided the internal resistance of the fibers is very high as compared to the resistance of the external shunting circuit. This is usually true as a first approximation, for the electrical resistance of a nerve fiber is of the order of 100 megohms per centimeter of length (cf Hill). Of course the resistance varies inversely as the cross-section of the fiber, and it is a well established fact that in a nerve containing fibers of varying diameters, like most mixed sensory and motor nerves, the individual fibers contribute to the total action potential quite accurately in proportion to their cross-sectional areas (Erlanger and Gasser). The relation of magnitude of action potential to size of fiber is exactly what we should expect, whether we think in terms of the internal resistance of the source or in terms of the shunting effect of one fiber on the potential of another.

Although generation of the potentials in nerve fibers is fundamentally different from the generation of piezo potentials in the hair-cells (see Chapter 14), the same electrical laws must

govern the summation of the effects of individual elements in both instances. In each instance there appears to be some effective addition of the potentials of elements which anatomically are arranged in parallel. In each instance the electrical circuits are complex, and we cannot safely assume that the addition of potentials will always be strictly linear. Furthermore, we must always remember that cells or fibers remote from the recording electrodes will contribute less to the observed potential than similar cells or fibers close to the electrodes.

ACTION POTENTIALS IN RESPONSE TO COMPLEX STIMULATION MASKING

When the ear is stimulated simultaneously by a series of clicks and a pure tone, the aural microphonics show a simple summation of the electrical waves which would be produced separately by each of the two stimuli. The only limitations to precise summation are those imposed by nonlinear distortion at high intensities. In sharp contrast to the microphonics, however, the action potentials, in response to clicks, decrease in size when a masking tone or noise is added. The degree of reduction of the action potentials depends upon the relative intensities of click and masking sound, and is greatest when the intensity of the clicks is near threshold. Figure 147 (p. 382) shows the effects of a masking noise on the response to clicks recorded from the round window.

The action potentials evoked by a click may be partially masked by tonal stimulation. Figure 158 shows that the degree of masking produced by the tone depends upon the phase relation of click to tone. The greatest reduction of the click response results when the click occurs at the peak of the action potential wave evoked by the tone. If the click response occurs immediately before the tonal wave, the action potential of the click is fully developed, while that of the tone is partially masked. The effectiveness of a tone in masking a click is also a function of its frequency and of its intensity.

The action potentials set up by tonal stimulation may be very effectively masked by simultaneous stimulation with a

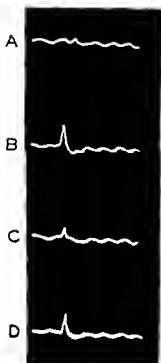


FIG 158 Oscillograms of the action-potentials of the auditory nerve in response to combined stimulation by clicks and by a 500-cycle tone. Both click and tone are about 30 db above threshold.

A The first wave of the click response is almost completely masked, but the second wave is unmasked.

B The first wave is unmasked and one wave of the tonal response is largely masked. The second wave of the click response is much reduced.

C and *D* show intermediate degrees of masking. (Derbyshire and Davis 2)

masking noise which has a wide frequency spectrum (Fig 150). Masking of the response of one pure tone by another can also be demonstrated, although less dramatically. Quantitative studies of the masking of tones, comparable to those carried out by psychophysical methods (see Chapter 8), have not been attempted because of the difficulties and uncertainties of measurement of the action potentials.

The reduction of the neural response to one sound by simultaneous stimulation with another depends upon, and is a necessary consequence of, the refractory period of nerve fibers. When one sound wave has stimulated a nerve fiber, a second wave which follows it within the functional refractory period is unable to set up an impulse and is physiologically ineffective, as far as that particular nerve fiber is concerned. Forbes has aptly referred to this situation as the "line busy effect." The degree of masking of the response to one sound by another gives a method for determining what proportion of nerve fibers the two responses share in common, for it is obvious that this type of interference can arise only when the two stimuli compete for the *same* nerve fibers. The "line busy effect" probably underlies the psychological masking of one tone by another,

or by a noise, although we need not assume that it is the *only* mechanism involved

The different behavior of the aural microphonics and the action potentials in response to complex stimulation is one of the simplest and most direct demonstrations of their fundamentally different characters. The microphonics summate, the action potentials show masking. The test of masking by a hissing sound readily identifies the neural components in a mixed response such as that obtained from an electrode on the round window.

INTERPRETATION OF THE PHASE-CHANGE BEAT

We are now in a position to consider a series of experiments which were designed to test the resonant properties of the inner ear, and reveal the origin of the electrical activity of the cochlea. If an observer listens to a steady tone whose phase is abruptly shifted by 180° , he hears a discontinuity in the sound. The discontinuity has been variously described as (1) a momentary period of silence, termed the *phase-change beat* (Hartridge), (2) a click superimposed on a steady tone, and (3) a momentary increase of loudness following immediately after the change of phase (Hartshorn). The momentary period of silence has been interpreted as revealing the presence in the ear of a tuned resonant structure which is less than critically damped. The behavior of the ear is assumed to be analogous to that of a vibration galvanometer driven by an alternating current at the frequency to which the galvanometer is tuned. When the phase of the current is abruptly shifted by 180° , the amplitude of vibration of the galvanometer dies down to zero and then builds up again in opposite phase.

When the cochlear microphonics and the nerve impulses of the auditory pathways are recorded during an abrupt change of phase of 180° , it appears, as shown in Fig 159, that the cochlear microphonics reproduce the change of phase with considerable fidelity, whereas the action potentials do not. The action potentials appear to die down momentarily and then

increase again in opposite phase; and they often show, in addition, a large transient wave resembling the on-effect or the response to a click

The difference in the records of microphonics and action potentials raises the question of whether the microphonics are generated by the same vibrating structure that initiates the nerve impulses. Hallpike, Hartridge, and Rawdon Smith concluded that the two electrical phenomena—microphonics and action potentials—are not traceable to the same vibrating structure. Despite the care and ingenuity of their argument, an alternative explanation of the observed facts appears possible

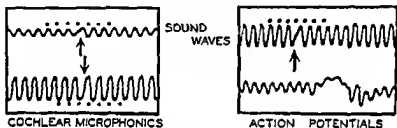


FIG 159 Oscillographic records of sound waves, of cochlear microphonics, and of action potentials from the mid brain. The phase of the sound waves is shifted by 180° at the points indicated by the arrows. The frequency is 1024 cycles. (For further explanation see text.) (After Hallpike, Hartridge, and Rawdon-Smith. By permission of The Royal Society of London.)

A change of phase of 180° is the equivalent of starting, in opposite phase, a second tone of the same frequency and of double the amplitude of the original tone. The irregularity of the action potential record is probably due primarily to what is equivalent to the on effect of this second tone. The on-effect stimulates nerve fibers over a wide area of the basilar membrane, and the corresponding nerve impulses undoubtedly form the basis of the click heard by many observers when the phase of the tone is changed. It is impossible to decide from records of the action potentials whether the diminution of the action potential waves which follows the phase-change represents a period of reduced neural activity, or whether it is actually a period in which many impulses are initiated by the on-effect but in which the nerve impulses are not synchronized with one

another. The response of the nerve fibers is further complicated by the refractory period of the fibers. The new out-of-phase sound waves probably find many of the fibers refractory, first, because of stimulation by the last of the in phase sound waves, and, second, because of stimulation by the widespread disturbance of the basilar membrane caused by the on-effect of the second tone. In other words, the combination of refractory period and on effect may temporarily mask the new tone. The cochlear microphonic, on the other hand, can reproduce the phase-change with greater accuracy than is possible for the action potentials, because it is not all-or none in character, and its continuity is not interrupted by a refractory period.

The most satisfactory explanation of all of the effects of an abrupt change of phase is to assume that the basilar membrane is sufficiently damped to allow it to follow such a phase shift with high fidelity, as revealed by the cochlear microphonics, and that the reduction of amplitude of the action potentials is due to asynchronous response to the on-effect, to the refractory period of the nerve fibers, and to the resulting masking of nerve impulses. If these assumptions are justified, it is not necessary to abandon the theory, which accords so well with so many other experimental observations, that the cochlear microphonics arise as a piezoelectric effect in the hair-cells of the organ of Corti and that the impulses in the fibers of the auditory nerve are initiated by a chemical process originating in these same hair cells.

The ability of the cochlear microphonics to follow the phase shift, without showing evidence of dying out to zero and starting up again in the new phase, means that the microphonics are generated by a mechanism which is very nearly critically damped. That the basilar membrane should be so highly damped argues strongly against the resonance theory of hearing (see p. 360) and suggests a place theory based on the principle presented in Appendix II.

CHAPTER 18

NERVE IMPULSES IN THE HIGHER AUDITORY PATHWAYS

IN OUR inquiry into the physiology of hearing, we have studied the mechanics of the ear, the generation of the aural microphonics, and, finally, the impulses in the auditory nerve. At each stage of the process we have sought to relate the activity of the auditory mechanism to the dimensions of the stimulating sound. Our ultimate objective, of course, is to determine how the characteristics of our auditory experiences are imposed by the nature of the peripheral mechanism of sense organ and nerve. We want to know the relation between the mechanical activity of the cochlea, the impulses in the auditory nerve, and the various subjective attributes of sound. But the problem of psychophysiological correlation does not end at the periphery. We face the additional problem of relating our sensory discriminations to the objective phenomena observable in the central nervous system.

THE GROSS ANATOMY OF THE AUDITORY PATHWAYS

From the point of view of psychophysiology, it is not necessary to describe in great detail the anatomy of the various nervous pathways within the central nervous system. The justification for this apparent neglect of facts which may be found in various anatomical works is not that anatomy is unimportant, but rather that our knowledge of the physiological activity of the various tracts is so slight that most of the anatomical detail stands unrelated to other data and does not appreciably illuminate the problem of psychophysiology which is our central concern. Nevertheless, purely anatomical considerations may set sharp limits to physiological speculation. For example, it has been suggested from time to time that the saccule may

play some part in audition. Anatomical studies (Lorente de No, 2) make this hypothesis untenable, since the nerve fibers from the saccular macula connect with the centers and pathways involved in the regulation of equilibrium but make no connection with those involved in the function of hearing*.

The essential features of the anatomy of the pathways between the auditory nerve and the cerebral cortex are presented in the form of a simplified schematic diagram in Fig 160. The cell bodies of the *primary neurons* constituting the auditory nerve are located within the modiolus of the cochlea. The primary afferent neurons all terminate in the cochlear nucleus, a mass of 'gray matter' located in the dorsal and lateral portion of the medulla oblongata at the point of entry of the auditory nerve. Here all the primary neurons form synaptic connections with *second-order neurons*. The diagram illustrates the pathways of these neurons to the *inferior colliculus* and to the *medial geniculate body*. In the diagram of Fig 160 no single neuron is represented as extending the entire distance from the cochlear nucleus to the medial geniculate body. Certainly most, if not all, of these pathways are interrupted by a synapse somewhere along the way. We shall see that physiological evidence supports this view. In man, most of the fibers leaving the cochlear nucleus cross the midline and proceed forward, in a tract known as the *lateral lemniscus*, to the *thalamic nuclei* on the opposite side. There are in addition, however, a small number of homolateral connections between the cochlear nucleus and the higher centers. The *third-order neurons* of the auditory pathways all converge in the medial geniculate body, which is the final relay station on the auditory path to the cerebral cortex. The medial geniculate body also receives fiber tracts from other sensory systems, as well as from the cerebral cortex, and it therefore appears to be not only a relay station but also an integrating and coordinating mechanism.

Fourth-order neurons connect the medial geniculate body

* A tiny bundle of nerve fibers connecting the saccular macula directly with the spiral ganglion in the cochlea has however been described in man (Hardy). Cf. also the work of Ashcroft and Hallpike on the function of the sacculus in the frog.

with the cerebral cortex by way of the auditory radiations. The best accounts of the connections and arrangement of these neurons (Poljak, Walker) are based upon experiments on

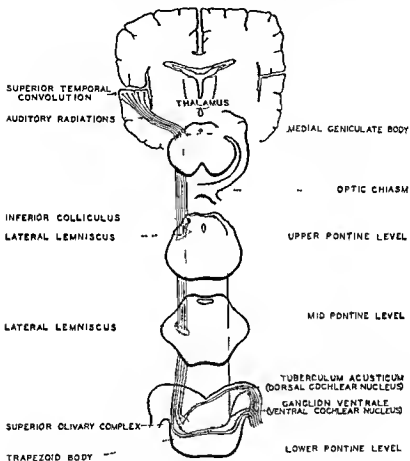


FIG 160 Simplified diagram of the auditory pathways. The diagram indicates successive transverse sections through various levels of the brain-stem, except for the upper part of the upper level. This upper level represents a vertical section through the cerebral hemispheres, so placed as to intersect the cross-sectional level of the upper mid-brain in the region of the medial geniculate body.

Only the neurons of one auditory nerve and their main connections are represented, although the auditory nervous system is actually bilaterally symmetrical. Only one pathway of each type has been represented and no attempt has been made to indicate the relative numbers of the different types of neurons illustrated. (After Rasmussen.)

monkeys (*Macacus*), but the description is adequate as a first approximation for the human brain as well. The auditory radiations resemble a fan, with its handle at the medial geniculate body, and pass into the white matter of the superior temporal convolutions of the cortex as a thin sheet of nerve-fibers. The radiations also include corticofugal fibers running from the cortex back to the medial geniculate body. Only a few of the afferent fibers of the auditory radiations reach the convex face of the temporal lobe. Most of the fibers enter a small region in the posterior half of the horizontal wall of the Sylvian fissure (Fig. 161), which represents what Poljak terms "the nuclear or focal zone" of the entire auditory cortex. Apparently all

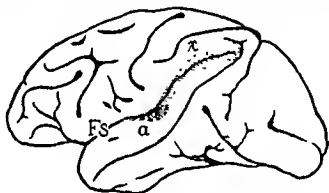


FIG. 161 Diagram of the auditory projection area in the monkey (*Macacus*)

Fs—Sylvian fissure

a—dark shading, the area receiving fibers of the auditory radiations from the medial geniculate body. This area extends deeply into the Sylvian fissure

x—light shading, the area receiving other afferent fibers which apparently do not belong to the auditory radiation (Poljak, 2)

the auditory impulses which reach the cerebral cortex must pass through the focal zone and thereafter be distributed to surrounding areas. Other afferent fibers from the midbrain which do not belong to the auditory radiations are distributed along the entire Sylvian fissure. None of the surrounding temporal cortex appears to receive any fibers from the subcortical nuclei. Walker describes the focal zone very specifically as an area 6 to 8 mm in length and 4 mm in width, sharply

bounded, and possessing distinctive features in the character and arrangements of the cells of which it is composed. It lies just mesial to Brodmann's area 22.

The projection from the medial geniculate body upon the cortex shows a precise point-to-point relation. The arrangement of the cells in the medial geniculate body and of the fibers in the auditory radiations is extremely regular and orderly. Figure 162 shows the relation, demonstrated by Walker, between portions of the cortical auditory area and the medial

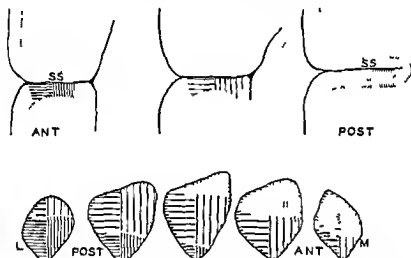


FIG 162 Schema of the projection of the medial geniculate body (below) upon the cortical auditory area (above) Each of the variously shaded portions of the geniculate body projects to the similarly marked portion of the cerebral cortex

Ant — anterior

M — medial

SS — Sulcus sylvii

L — lateral

Post — posterior
(Walker, 2)

geniculate body. The precision of the relations suggests the possibility of a fixed and stable projection of the organ of Corti upon the cerebral cortex.

THE MICROSCOPIC ANATOMY OF THE COCHLEAR NUCLEUS

The finer microscopic structure of the cochlear nucleus deserves a brief description, if only to counteract the impression of

simplicity unavoidably conveyed by such a diagram as Fig 160. The bewildering complexity of the nucleus must be thought of as typical of the cerebral cortex and of the gray matter of the central nervous system in general. The arrangement of the auditory fibers as they enter the cochlear nucleus and distribute to the various portions of this structure has already been pictured and described in Fig 146 (p 378). A closer inspection of the elements composing the first central station of the cochlear fibers shows that these elements are much more complicated structures than is generally assumed. Each cochlear fiber makes connections with numerous cells. These cells are grouped in no less than thirteen regions, in which different types of neurons, arranged in characteristic fashion, are found (Lorente de No, 2). Although numerical data are not available, it is probably safe to state that in the primary cochlear nuclei no less than forty or fifty types of neurons are present, and that each cochlear fiber establishes connections with many hundreds, and perhaps even thousands, of cells. The cells may be divided into classes. For example, there are cells with long and cells with short axons. The former cells convey impulses which are carried from the cochlear nucleus to higher centers, and may be called *efferent cells*, but the short axons of the second type of cell do not extend beyond the boundaries of the cochlear nucleus itself. They make interconnections within this nucleus, and finally impinge upon cells with long axons. The cells with short axons which remain entirely within the boundary of the nucleus have frequently been called *intercalary* or *internuncial neurons*. These names, however, are to some extent misleading because the cells with short axons are not arranged 'in series' between the primary afferent fibers and the efferent neurons, but are arranged in the form of alternative routes 'in parallel' with the direct synapse between the first-order and the second-order neurons. The physiological significance of this type of double connection between the primary afferent fibers and the higher order neurons is, as yet, quite obscure, but it appears to be the type of connection which is characteristic of all parts of the gray matter of the central nervous system. When we speak of *first order*, *second order*, and *third-order neurons*, we have in

mind the simple concept of the diagram in Fig 160, and we do not take account of the short accessory neurons within the nuclei. The designation, second order neuron, means that an impulse coming from the periphery must have traversed *at least* one previous neuron and synapse before arriving at this, the second order neuron. Third order implies that *at least* two previous neurons and synapses have been traversed, and so on. We shall see that experimental observations indicate that transmission may be, and often is, as direct as this. The short accessory neurons, however, give almost limitless opportunities for interconnection and interplay between the various fibers of the auditory pathways.

NERVE IMPULSES IN THE COCHLEAR NUCLEUS

No very systematic study of the nerve impulses in the cochlear nucleus has been carried out. An electrode placed on the surface of the cochlear nucleus detects activity much like that in the auditory nerve. This activity usually includes an admixture of aural microphonics conducted along the auditory nerve and the meningeal covering of nerve and brain. Coaxial electrodes inserted into the substance of the nucleus detect large and complex responses to sounds. The character of the responses depends upon the exact position of the electrodes, but the responses are often of higher voltage than those obtained from the auditory nerve. It is generally true that the voltages obtained from gray matter, which contains the bodies of nerve cells and the synaptic junctions, are larger than those obtained from white matter, which consists of axons alone.

NERVE IMPULSES IN SECOND ORDER AND THIRD ORDER NEURONS

It is unnecessary to tabulate all the various anatomical structures of the midbrain from which auditory impulses have been detected. The list includes all the structures named in Fig 160. Furthermore, practically all the structures from which auditory activity has been reported belong to anatomically recognized auditory pathways.

The most complete investigation of the nerve impulses in auditory pathways has been made in the cat by Kemp, Coppée, and Robinson. The following account is based almost entirely on their work.

The trapezoid body is a convenient structure in which to observe the impulses in second-order auditory fibers. Its response to stimulation of the ear by low tones is a series of volleys of action potentials synchronized to the frequency of the sound waves. The electrical pattern closely resembles that of the first order neurons of the auditory nerve. The threshold is as low as, and frequently 10 to 20 db lower than, that for the aural microphonics simultaneously recorded from the round window.

Upper Limit of Synchronization The upper limit of frequency for synchronization is about 2500 cycles, and this limit is attained only under strong stimulation. Apparently the impulses can maintain synchronization through one, and occasionally two, stages of alternation. Thus, the limit is lower than it is in the auditory nerve. This lower limit may be due to a tendency for the impulses to become more dispersed in time as they traverse synapses, or to a tendency of second-order neurons to respond irregularly when bombarded by impulses at a frequency too high for the neuron to follow. We may note here that the upper limit of synchronization in the third-order neurons of the inferior colliculus may be as high as 1500 cycles, but more commonly it is near 1000 cycles. It therefore appears that distinct alternation no longer readily occurs when two synapses have been traversed, or else that the alternation becomes completely obscured by temporal dispersion. This failure of synchronization at frequencies above about 1000 cycles is important evidence against the adequacy of a frequency theory of pitch perception (p. 359). It may also be significant that binaural beats may be heard only when the generating tones are not higher than 800 cycles (p. 172).

THE AMPLITUDE OF ELECTRIC RESPONSE

The amplitude of the electric response at a given point in the trapezoid body increases with increasing intensity of the

stimulating tone, but, for a given position of the coaxial electrodes, the increase may be quite irregular (Fig 163). The same kind of irregularity is found also in the response of third order neurons, and different electrode positions give different curves for one and the same tone. The irregularities are probably due to the fact that the coaxial electrodes detect highly localized activity at specific positions in an anatomically complicated nerve tract. The situation is similar to that found in

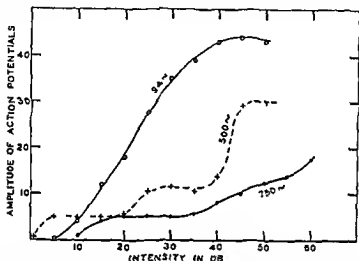


FIG 163 The amplitudes of action potentials from a point in the lateral lemniscus as a function of the intensity of the stimulating tones. Intensity is expressed in decibels above an arbitrary threshold. The amplitudes increase as additional fibers are activated but the increase is often irregular because the pick up of the coaxial electrodes is confined to a small area selected at random in a large complex tract. (After Kemp, Coppée, and Robinson.)

the auditory nerve, but the effect of slight differences in the position of the electrodes is even more critical in the trapezoid body. There underlies this irregularity, however, the important implication that the impulses generated by a given tone at a given region of the basilar membrane are assigned for conduction to certain well-defined groups of fibers.

The Response of Second and Third Order Neurons to Impulsive Stimuli. To impulsive stimuli, such as clicks, the response of second and third-order neurons is complex, like

the response of the first-order neurons of the auditory nerve. The *F*, *G*, and *H* waves described in Chapter 16 can usually be recognized in the higher pathways. They show here the same relative latencies and are masked by the same tones as in the peripheral nerve. In the higher centers, however, the shape of the action-potential wave as a whole is somewhat more variable as a function of the position of the electrodes. Figure 164 shows how, with a given placement, the amplitude of the

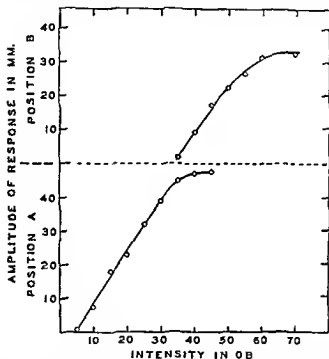


FIG 164 Amplitude of action potentials of the lateral lemniscus (third order neurons), as a function of increasing intensity of a click. The apparent maximum obtained at position *A* is probably due to localized recording and is no indication that additional fibers are not activated at higher intensities, for from position *B* in the same preparation a response is obtained which has a considerably higher threshold and which continues to grow in amplitude over a correspondingly higher range of intensity (After Kemp, Coppée, and Robinson)

F wave increased over a range of 30 to 40 db and then attained a maximum. At a nearby electrode-position the threshold was 30 db higher than at the first, but the amplitude increased

over an intensity range of 30 db above *its own* threshold. Over this range the response at the first position remained constant. It is evident that the total response in the nerve tract as a whole increased over the entire range, and that the limit reached at the first electrode position was fictitious, in the sense that it resulted from the localizing power of the coaxial type of electrodes.

THE LATENCY OF NERVE IMPULSES IN THE HIGHER PATHWAYS

Figure 165 shows the latencies of nerve impulses in first order, second-order, and third-order neurons in relation to one another, and also in relation to the strength of the stimulus. The measurements were made on the earliest (F) wave in response to clicks of various intensities. For strong stimuli, the latency of this wave in the auditory nerve is 0.9 msec with respect to the beginning of the cochlear microphonic. In the second-order neuron it is 2.2 msec, at the same intensity of stimulation. The difference of 1.3 msec must be attributed to (a) conduction time and (b) synaptic delay in the cochlear nucleus. A reasonable maximal allowance for conduction time is 0.5 msec. We therefore arrive at a value for the synaptic delay of about 0.8 msec.

The latency between second order and third-order neurons lies between 1.3 and 1.7 msec. When we again make allowance for conduction time we find that the synaptic delay in the olivary complex, or in the nucleus of the lateral lemniscus, must also be at least 0.8 msec. This value, in fact, appears to be a good average value for the shortest synaptic delays which we encounter, and is nearly the same as the 0.6 msec given by Lorente de Nó (3) for the minimal delay in the oculomotor nuclei. Also the delay between the hair cells and the primary auditory neurons is usually at least 0.6 msec (p. 385).

It will be seen that the curves in Fig. 165 fall into three groups, separated in latency by 1.2 msec or more, corresponding to the different orders of neurons. The systematic and step-like increase in latency gives a basis for deciding, in doubtful

cases, whether a response from a particular region represents the activity of a neuron of the first, the second, or the third order, for a minimal delay of 0.6 to 0.8 msec appears to be a general feature of synaptic transmission. On this basis it ap-

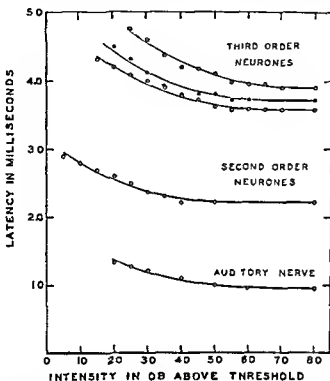


FIG. 165. A comparison of the latencies of action potentials at five positions in the auditory pathways in a cat. The auditory nerve-responses were recorded from the round window. The second-order neurons were fibers of the trapezoid body and the third-order neurons were fibers of the lateral lemniscus. Note that the latent period decreases with increasing intensity of the stimulating click until it reaches a final minimal value (cf. Fig. 149) and that the change in latency is greater in the second and third-order neurons than in the fibers of the auditory nerve. The threshold in this figure is arbitrarily chosen as an intensity level slightly lower than that which elicited responses from the trapezoid fibers. (After Kemp Coppee, and Robinson.)

pears that all pathways which reach the level of the midbrain have been interrupted by synapses at least twice—once in the cochlear nucleus and again in the olivary complex or the nucleus of the lateral lemniscus—for no impulses have been found in

the medial geniculate body with latencies brief enough to belong to second-order neurons

From fourth-order neurons, in the brachium and medial geniculate body, responses to clicks may sometimes be obtained. Their latencies, although not shown in Fig 165, are 4 to 5 msec. From the auditory cortex, under favorable conditions of anesthesia, similar responses appear with a minimal latency of about 8 msec.

Returning to Fig 165, we observe that the curves for all orders of neurons show a diminution of latency with increase of stimulus intensity. The decrease is greatest for sounds near threshold. In the primary neurons of the auditory nerve the decrease is from 1.3 msec to 0.9 msec, that is to say, 0.4 msec. The decrease amounts to 0.7 msec in the second order and third order neurons. Evidently there is a significant shortening of the delay in the cochlear nucleus as a result of increasing the number of active fibers. A similar diminution of synaptic delay regularly occurs at the junction between second order and third order fibers, as the downward sweep of the upper curve clearly shows. By the time third or fourth-order neurons are reached, the cumulative effect of the shortening of all the synaptic delays is considerable.

The fourth order neurons connecting the inferior colliculus to the medial geniculate body and the neurons of the auditory radiations are difficult to study, for the higher synapses of the auditory pathways are more or less completely blocked by the surgical anesthesia necessary for such experiments. In some cases impulses have been detected, latencies measured, and the limit of synchronization determined, but our knowledge concerning these neurons is quite meager. The upper limit of synchronization in the auditory radiations appears to be far below 500 cycles, and may be as low as 100 cycles, which is the highest frequency of response yet recorded from the auditory cortex. Single widely separated clicks may yield large well synchronized responses from these higher-order neurons, but fatigue or equilibration appears early, and at low frequencies, and the response to a steady tone consists chiefly of an on-effect,

and perhaps also an off-effect, with comparatively slight, usually asynchronous, activity while the tone continues. In this respect the activity of the auditory radiations resembles that of the cortex more closely than it does that of the third-order neurons. Loss of precise synchronization of impulses and great vulnerability to anesthetics seem to characterize the synapse between third and fourth-order neurons, and also the synapses of the cortex. The synapses of the olivary complex, on the other hand, are about as resistant to anesthetics as are those of the respiratory center, and those of the cochlear nuclei are even more resistant.

RELATION OF LATENCY TO AUDITORY LOCALIZATION

The earlier arrival of larger volleys of impulses at the centers of the midbrain (Fig. 165) is interesting in connection with the phenomena of the apparent direction of the source of a sound. In Chapter 6 we found that the earlier arrival of a click at one ear causes us to refer the source of the sound to that side. A similar effect is produced by making the sound louder in one ear, and a delay in arrival at one ear can be offset, to some extent, by increasing the intensity of the later sound (Trimble 4).

The relations presented in Fig. 165 suggest that a difference in intensity may, in the higher pathways, be physiologically equivalent to a difference in time. Such a reduction of intensity to time would simplify the theory of localization, but the experimental data on localization do not justify a complete reduction of this sort. Furthermore, measurement of the smallest increase in intensity of a tone in one ear, necessary to shift the apparent source of a tone to the side of that ear (Fig. 72, p. 170), shows that the necessary increase is less than 1 db at medium intensities and that it increases at lower levels. The curves of Fig. 165 suggest, however, that the necessary increase of intensity should be smaller at low levels, instead of larger. In other words, no simple relation between time and intensity, as factors in localization, can be derived from our present data.

THE EFFECTS OF BINAURAL STIMULATION

The cochlear nucleus gives little or no electric response to sound waves delivered to the opposite ear, provided bone conduction and other forms of direct spread of the stimulus to the homolateral cochlea are scrupulously avoided. Likewise in the trapezoid bodies, the activity is determined by the stimulation of the ear from which the tract originates, but, by the time the superior olivary complex and lateral lemniscus have been reached, there is a complete mingling of homolateral and contralateral fibers from the two cochlear nuclei. In the cat, there seems to be approximately the same number of crossed and of uncrossed fibers in the lateral lemniscus. At any given level the homolateral and contralateral neurons are of the same order, that is to say, homolateral second order neurons mingle with contralateral second order neurons, third order with third order, and so on. At any given point, where homolateral and contralateral fibers are mingled, the latency of response to stimulation of the right ear is equal to that following stimulation of the left ear. In other words, impulses originating simultaneously in the right and left ears pass simultaneously up both the right and left lateral lemniscus. In the right lateral lemniscus the impulse originating in the right ear does not lead in time the corresponding impulse from the left ear (Kemp and Robinson).

The impulses from the two ears run in separate fibers of the lateral lemniscus quite independently of one another. If the two ears are stimulated simultaneously, the latency of response in the lateral lemniscus is the same as that following stimulation by the same intensity delivered to either ear alone. Although doubling the intensity of stimulation of one ear may appreciably reduce the latency of the response (see Fig. 165), ~~the simultaneous stimulation of the opposite ear by the same~~ intensity does not cause any change in latency. Nevertheless the amplitude of the total response at the lateral lemniscus is increased, and, at least at low intensities, the total response may quite accurately equal the sum of the homolateral and contralateral responses taken separately. Presentation of a tone to

one ear and a click to the other does not result in masking, and there is no evidence of masking of one click by another delivered slightly earlier to the opposite ear. In the language of neurophysiology, we can say that there is little if any facilitation, occlusion, or interaction of any sort between the homolateral and contralateral fibers of the auditory pathways at the levels of the cochlear nuclei or of the superior olivary complex. The pathways are anatomically mingled, but physiologically independent, at least up to and including the third-order neurons. Whether or not binaural interaction occurs in the inferior colliculus or the medial geniculate body has not yet been determined.

EFFECTS OF OPERATIVE DAMAGE TO THE AUDITORY PATHWAYS

A totally different experimental approach to the problem of the interaction between, and the relative importance of, bilaterally symmetrical portions of the auditory system is the surgical removal of one or more parts of the auditory pathways. Such operations have been performed (Brogden, Girden, Mettler, and Culler) upon dogs that had previously been trained by the method of conditioned reflexes to respond to the faintest audible tone. Their auditory acuity was determined prior to operation, immediately following it, and also a considerable period later. This type of animal experimentation most nearly resembles psychological measurements made upon human beings, and gives a fair indication of the effect of any particular operation upon the auditory acuity of the animal.

Removal of the cerebral cortex of a single hemisphere is followed by a comparatively small loss of acuity. At 1000 cycles, the loss is only 2 to 5 db, which is a barely significant loss (see Fig 166 *A*). The loss is practically the same whether the right or the left hemisphere is removed. Removal of the entire cortex, however, produces an enormous loss of hearing, of from 70 to 75 db (Fig 166 *B*). It is of interest that the conditioned auditory response can be elicited at all after total removal of the cortex. This finding is contrary to a very gen-

crally accepted belief that the cerebral cortex is necessary for the performance of conditioned reflexes. Apparently the cortex is not strictly necessary for conditioning, provided stimuli of sufficient intensity are employed.

Destruction of one cochlea in an otherwise intact animal is followed by a hearing loss of about 3 db (Fig. 166 C). This

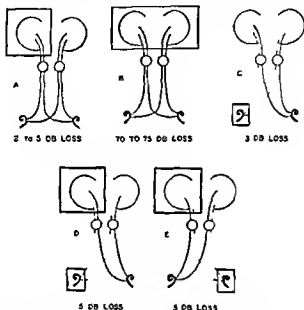


FIG. 166. Diagrams showing the hearing loss which results from removal of various portions of the auditory mechanism in dogs.

A — removal of one cerebral hemisphere.

B — removal of both cerebral hemispheres.

C — destruction of one cochlea.

D — removal of one cerebral hemisphere and destruction of the homolateral cochlea. Hearing here depends upon the *uncrossed* fibers of the opposite lateral lemniscus.

E — removal of one cerebral hemisphere and destruction of the contralateral cochlea. Hearing here depends upon the *crossed* fibers of the right lateral lemniscus. The amount of hearing loss is the same in D and E.

corresponds quite well with human experience that binaural listening is more sensitive than monaural (see p. 52). Destruction of both cochleae naturally produces total deafness.

In an animal from which one cerebral hemisphere has

already been removed, the destruction of one cochlea causes an additional drop of 10 db (Fig 166 D) It is immaterial whether the cochlea destroyed is on the same or opposite side as the remaining cerebral hemisphere (Fig 166 E) The equivalence of the two ears, when only one cerebral hemisphere is intact, shows that the crossed and the uncrossed central connections are equivalent with respect to auditory acuity The loss of hearing is the same whether the impulses reach the remaining cortical hemisphere by way of crossed or uncrossed fibers That there is an equivalence between crossed and uncrossed fibers coincides with the conclusions derived from the study of the nerve impulses in cats, but we have no assurance that these conclusions can be carried over to man, in whom there may be somewhat different proportions of crossed and uncrossed fibers in the lateral lemniscus

THE EFFECTS OF DAMAGE TO THE MEDIAL GENICULATE BODIES

We have already seen that the arrangement of neurons in the medial geniculate bodies and the auditory radiations is notably systematic and orderly (cf Fig 162) The arrangement apparently corresponds to the arrangement in the auditory nerve and cochlear nucleus, for localized surgical lesions cause differential loss of sensitivity for particular tones Using a Horsley Clarke stereotaxic instrument, Ades, Mettler, and Culler introduced an electrode through a small hole in the skull and on through the cerebral hemisphere into the medial geniculate body, where they produced a small localized lesion No significant damage was caused to other parts of the brain by this operation The cats had previously been conditioned to respond to the faintest audible tone After the operation, hearing losses of as much as 20 db were found for particular tones, and the tones for which acuity was diminished corresponded systematically to the locations of the lesions These locations were checked by microscopic examination

The results of these experiments demonstrate that a particular faint tone excites a restricted region within the geniculates

and that the location of the excited region depends upon the frequency of the tone. The several foci are disposed in a spiral within the geniculates, as follows

<i>Frequency</i>	<i>Location*</i>
125	Base (ventral side)
250	Base (ventral side)
500	Medial quadrant
1000	Posterior quadrant
2000	Lateral quadrant
4000	Rostral quadrant
8000	Dorsal region

The disposition of the auditory pathways in the geniculates seems, therefore, to conform with the organization found elsewhere in the auditory mechanism

THE AUDITORY CORTEX

The highest level of the nervous system is the cerebral cortex. We can trace the auditory pathway from the cochlea to a particular region near the Sylvian fissure of the temporal lobe, but from there on the possible pathways and interconnections are so numerous that none can be designated specifically as auditory pathways.

Clinically, we can recognize disabilities of hearing related to disease of the sense-organ, of the auditory nerve, and, more rarely, of the lateral lemniscus or other higher pathways. The usual disability manifests itself as a loss of acuity. Loss or malfunction of portions of the cerebral cortex, on the other hand, may give symptoms of quite another sort, such as aphasia, amnesia, etc., in which the patient hears the sounds but fails to associate their usual meanings with them. There may occur *a loss of meaning for all sounds, or only loss of meaning for words*. Or the patient may suffer from auditory hallucinations, and hear sounds or words for which there is no recognizable counterpart in the external world. Such hallucinations may

* The locations for the two lowest tones (125 and 250 cycles) have not been established as definitely as the locations for the higher tones.

sometimes be part of a more or less generalized spontaneous cortical excitation, as in an auditory 'aura' preceding an epileptic seizure

Further description and analysis of such conditions lie beyond the scope of this book, because at this cortical level new difficulties and complexities appear. On the physiological side, we can no longer trace synchronized nerve impulses, and on the psychological side we are uncertain as to what aspect of experience to choose in the search for discriminations which may be correlated with differences in physiological activity. It may be profitable, nevertheless, briefly to describe the electrical phenomena of the cerebral cortex, for, whatever their psychological correlates may be, they are closely related to the activities of the sensory pathways

ELECTRICAL ACTIVITY OF THE CORTEX

The cerebral cortex is the seat of continuous, more or less rhythmic, fluctuations of electric potential whose periods are of the order of tenths of a second. The electrical waves are much slower than the action potentials of nerve trunks, and may or may not represent a different type of underlying biochemical and biophysical activity. Much of the activity appears to originate spontaneously within the central nervous system and not to be conditioned directly by, or dependent upon, incoming sensory impulses (see Jasper for a review of these phenomena). The spontaneous background of activity may be increased or, more commonly, decreased by sensory stimulation, and the activity is profoundly modified by general internal conditions, such as oxygen supply, anesthesia, and sleep. The patterns of spontaneous activity are broadly similar in voltage wave form, and rhythm, in all parts of the gray matter which have been studied, but there are slight differences in pattern which are more or less characteristic of particular anatomical areas. These differences may be correlated with differences in microscopic structure of the gray matter and with differences in peripheral connections and physiological function, but their significance is, as yet, purely empirical and poorly understood.

Stimulation of a sensory pathway usually depresses the spontaneous activity in the corresponding cortical field with which that pathway is most directly connected, and it may depress or modify activity in other fields as well. In addition to these general effects, there is, at the beginning of stimulation, a well marked electric response in the corresponding cortical field. In order to see the response clearly we must either avoid the effects of anesthetics entirely, in order not to depress the response, or else anesthetize deeply enough to silence the background of spontaneous activity. Action potentials resembling on-effects are readily obtained in the optic area (area striata) and are present, but not so well developed, in the auditory area. In the cutaneous tactile area, the response to local contact with the skin is quite precisely localized to a small part of the sensorimotor cortex (Marshall, Woolsey, and Bard). If, in the ear, we think of a pure tone as stimulating locally a part of the basilar membrane, we might expect, by analogy, to find a correspondingly localized response in the auditory area of the cortex. However, such localization has not been directly demonstrated. If a sustained increase or decrease of electrical activity appears at all in response to a sustained tone, it seems to include the entire auditory area (Kornmüller). There is, on the other hand, a strong suggestion from the study of lesions of the temporal lobe, which have caused deafness in man, that perception of high tones depends upon the medial portion of the transverse temporal convolution and that perception of low tones is a function of the anterior and lateral portions of the same convolution (Pfeifer).

The response of the auditory area to a single click, and to the onset of a sustained tone, is a single electric wave, or action potential, which requires at least 3 msec to reach its maximum and which falls still more slowly. The surface of the cortex becomes relatively more electropositive during the response. The latency of this electric wave is at least 8 msec. The frequency of a pure tone is not reproduced, but a succession of sharp clicks, at frequencies up to 100 per second, may elicit a corresponding series of small action potentials. At higher

frequencies the individual waves can no longer be detected

All things considered, it is obvious that, until many more data are available, it is futile to speculate as to the relation between the electrical activity of the cortex and the psychological phenomena of hearing

THE PROBLEM OF PSYCHOPHYSIOLOGICAL RELATIONS IN HEARING

Although we have found it impossible to trace the physiological determinants of auditory sensation through the higher pathways of the cortex, we have not failed in our effort to discover the organic basis of many sensory discriminations. We have noted, from time to time, that the ultimate form of certain auditory responses is imposed by the nature of events in the middle ear, in the cochlea, and in the auditory nerve, and in some instances it has proved appropriate to relate psychological with physiological functions. An attempt, at present, to account for all psychological discriminations in terms of physiological processes is obviously premature, and explanations in this realm of psychophysiology must be cast in speculative form. Although speculation may be hazardous for the good repute of the speculator, it fulfills an important purpose when it serves to give perspective to a field of inquiry, or when it stimulates research designed to replace speculation by factual demonstrations. It has been in this spirit that occasional suggestions as to possible psychophysiological correlations have been ventured.

Two principles must guide all our efforts to relate psychological with physiological facts. (1) No discriminatory reaction to an auditory stimulus is possible unless there exists, at every stage of the auditory process, a differentiated pattern, one of whose aspects provides a basis for the reaction in question. On the other hand (2), the presence of a particular differentiated pattern does not insure that a discriminatory reaction will be possible, because differentiation at lower levels may become lost at higher levels. Thus the presence, in the auditory nerve, of impulses synchronized with the waves of the stimulus prob

ably does not furnish grounds for a subsequent discrimination, for the synchronization is apparently lost at later synapses, without there establishing a surrogate pattern whose differentiation reflects the frequency-aspect of the previous pattern.

The first of these principles—the requirement of adequate differentiation at each stage—does not mean that the crucial aspect of the pattern of differentiation underlying a later response will be obvious under our methods of analysis. It frequently happens that a discrimination rests upon a particular combination of one or more observable aspects of the earlier pattern. For example, ordinary methods of analysis show that a pure tonal stimulus can be adequately characterized in terms of the two aspects, frequency and intensity. The four discriminatory reactions which we call pitch, loudness, volume, and density are each based upon some particular combination of these two variables of the stimulus. The interaction of the stimulus with the human organism establishes neural patterns differentiated in at least four different ways, so that under different attitudes, or *Aufgaben*, four different types of reaction are possible. The attitude which we give an observer by way of an instruction to attend to a particular aspect of his sensations is of great consequence in this process, for it determines the character of the ultimate differentiation quite as much as does the stimulus itself. In this sense, the instruction, or the self-instruction, accepted by the listener can be regarded as part of the stimulus-pattern, although this part of the stimulus usually enters by way of another modality, or at an earlier time, and is not represented in the events which we record as electrical effects in the sense-organ and nervous pathways.

These general principles are basic to any understanding of the relations between the three aspects of the perceptual process which we somewhat arbitrarily distinguish as stimulus, neural activity, and response. Such principles must guide our future explorations of this vast and important field of research—a field in which our excursions have only just begun, but which holds rich rewards for man's irrepressible curiosity to know why

APPENDIXES

APPENDIX I

FORMULAS FOR MODULATION

Amplitude Modulation In the formula for a sinusoidal wave,

$$y = A \sin \omega t,$$

where ω is the angular velocity and t is time, let A , the amplitude of the wave, vary with time in such a way that

$$A = (1 + m \sin qt)$$

where m represents the amplitude of the modulation, and q is the angular velocity of the modulating wave. Then, if we let $A = 1$, substitution of (eq 2) in (eq 1) gives

$$y = \sin \omega t + m \sin \omega t \sin qt$$

Trigonometric reduction of this formula gives

$$y = \sin \omega t + \frac{1}{2}m [\cos (\omega t - qt) - \cos (\omega t + qt)]$$

Thus we see that there are present in a wave, whose amplitude is modulated sinusoidally, three frequencies. They are the original wave, or central band, and two side bands differing from the central band by an amount equal to the frequency of the modulation.

Frequency Modulation The following mathematical development (Ramsdell) will show how the frequency modulated wave may be represented as a spectrum of sinusoidal waves, having constant amplitudes and frequencies. If the frequency is not modulated (assuming a sinusoidal wave form), the amplitude of the wave is given at any instant (t) by the equation

$$y = A \sin \omega t \tag{1}$$

where A is the maximum amplitude and ω is the angular velocity of the generating vector, whose length is A . In this case the angular velocity is assumed to be constant. Frequency modulation requires, however, that the angular velocity be variable, and that the variability itself be a function of time. Thus $y = A \sin \omega t$ becomes $y = A \sin \omega$ (which is itself a function of time) t . When the angular velocity or its related measure, frequency, is varied in such a manner that the variation of frequency with time is sinusoidal, ω itself is a function of time and may be represented as

$$\omega = p + h \sin qt$$

where $p =$ the initial value of ω in the equation for the unmodulated wave, $h =$ amplitude of the frequency variation, $q =$ rate of frequency variation. The angle, θ , through which the vector, A , has rotated in time, t , may be expressed

$$\theta = \int_n \omega dt = \int_0^t (p + h \sin qt) dt$$

Thus

$$y = A \sin \omega t$$

becomes

$$y = A \sin \int_0^t (p + h \sin qt) dt \quad (2)$$

$$\begin{aligned} &= A \sin [pt - h/q \cos qt] \\ &= A \sin [(pt + h/q) - h/q \cos qt] \end{aligned} \quad (3)$$

In the trigonometric relation

$$\sin (x - y) = \sin x \cos y - \cos x \sin y,$$

let

$$x = (pt + h/q) \quad \text{and} \quad y = h/q \cos qt,$$

then (eq 3) becomes

$$y = A [\sin (pt + h/q) \cos (h/q \cos qt) - \cos (pt + h/q) \sin (h/q \cos qt)] \quad (4)$$

From the Fourier developments:

$$\cos (Z \cos \theta) = J_0(Z) - 2J_2(Z) \cos 2\theta - 2J_4(Z) \cos 4\theta + 2J_6(Z) \cos 6\theta \dots$$

$$\sin (Z \cos \theta) = 2J_1(Z) \cos \theta - 2J_3(Z) \cos 3\theta + 2J_5(Z) \cos 5\theta \dots$$

in which $J_n(Z)$ is the Bessel Function of the first kind and the n th order for the argument Z .

Substitute in (eq. 4) these equations for the products of trigonometric values, i.e., for $\cos (h/q \cos qt)$ in the first term and $\sin (h/q \cos qt)$ in the second term, and it becomes:

$$y = A \{ \sin (pt + h/q) \} \{ J_0(h/q) - 2J_2(h/q) \cos 2qt - 2J_4(h/q) \cos 4qt + \dots \} \\ - \{ \cos (pt + h/q) \} \{ 2J_1(h/q) \cos qt - 2J_3(h/q) \cos 3qt - \dots \}. \quad (5)$$

$$y = A [J_0(h/q) \sin (pt + h/q) \\ - 2J_1(h/q) \cos qt \cos (pt + h/q) \\ - 2J_2(h/q) \cos 2qt \sin (pt + h/q) \\ + 2J_3(h/q) \cos 3qt \cos (pt + h/q) - \dots]. \quad (5a)$$

The product of trigonometric values may be expressed as sums:

$$\cos x \cos y = \frac{1}{2} \cos (x + y) + \frac{1}{2} \cos (x - y)$$

$$\sin x \cos y = \frac{1}{2} \sin (x + y) + \frac{1}{2} \sin (x - y),$$

which further simplifies (eq. 5a),

$$y = A \{ J_0(h/q) \sin (pt + h/q) \\ - J_1(h/q) [\cos (pt + h/q + qt) + \cos (pt + h/q - qt)] \\ - J_2(h/q) [\sin (pt + h/q + 2qt) + \sin (pt + h/q - 2qt) \\ + \dots] \}. \quad (6)$$

An examination of (eq. 6) shows that when p is varied sinusoidally by the amount h at q times per second, frequencies are produced in addition to the one at p and lie on both sides of it. There are, mathematically, an infinite number of these sidebands, spaced by multiples of the rate of modulation ($p \pm nq$).

The relative amplitudes of the side bands are to each other as the numbers which express the Bessel coefficients and are determined by the ratio h/q . The smaller the value of the ratio, the smaller are the amplitudes of the side bands.

The value of h/q is used in entering a table of Bessel coefficients (Gray, Matthews, and MacRobert) in order to find the amplitude of the central frequency and of the various side bands. Examples of the sound spectra for different values of h/q are shown in Fig 167.

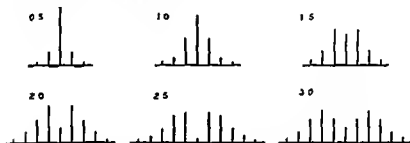


FIG 167 The relative amplitudes of the components produced by a frequency modulation in which the ratio of range to rate is as indicated on each plot. The components are spaced apart by a number of cycles equal to the rate of modulation. For the modulations represented here, the rate is assumed to be constant and the range variable.

The frequency modulation treated above is assumed to be sinusoidal with time. Van der Pol (2) has developed a series giving the coefficients (amplitudes) of the side bands in the case of a 'square topped' modulation, in which the frequency alternates abruptly between two values.

APPENDIX II

It has been customary to treat the mechanical properties of the cochlea from the point of view of a series of tuned elements. Thus Wegel and Lane proposed an electrical analogue of the cochlea consisting of a row of series resonant circuits connected in parallel but separated by an appropriate inductance. Such a circuit would simulate the properties of the cochlea, for the basilar membrane behaves *as if* it consisted of a row of tuned resonators. The behavior of Wegel and Lane's circuit could be described by an appropriate set of differential equations.

It is also possible, however, to treat the cochlea from the point of view of a hydraulic system contained in a vessel with elastic walls, and to apply to it the theory of propagated disturbances in media constrained by elastic boundaries. The differential equations then take on a different form. Reboul set up these differential equations on the basis of the assumption that a disturbance is propagated along a fluid column contained in a tube with elastic walls. The action of the cochlea would then be as follows. Movement of the oval window (stapes) starts a compression wave which travels toward the helicotrema. If the wave is sufficiently sharp (high frequency) so that the variations in pressure are not transmitted to the scala tympani through the helicotrema (see p. 276), we can regard the tube in which the propagation occurs as being the scala vestibuli. This canal is bounded above by a solid wall and below by an elastic wall—the basilar membrane. For a given frequency, one part of this membrane will vibrate more than any other. Furthermore, there will be a varying pressure gradient across the membrane which, in general, will not be in phase with the displacement of the membrane.

Then, if $y = f(x, t)$ represents the displacement of a point in the medium as a function of the distance x from the oval

window and of the time t , the velocity of the point is given by $u = \frac{dy}{dt}$. The relations between the pressure p and x and t are given by

$$\frac{1}{c^2} \frac{\partial p}{\partial t} + \rho_0 \frac{\partial u}{\partial x} = 0$$

$$\rho_0 \frac{\partial u}{\partial t} + \frac{\partial p}{\partial x} = 0$$

where ρ_0 is the density of the fluid and c is the speed of propagation of the pressure wave. The value of c could be calculated from the diameter of the cochlear canals and the elastic constants of its walls and of the fluid within it. (The formulas for dealing with this type of problem are used to calculate the speed of pulse waves in arteries.)

The values of the various constants necessary for an exact solution of these differential equations are not precisely known for the cochlea, but, by making certain reasonable assumptions, Reboul was able to show that the speed of propagation of the pressure wave along the basilar membrane is of the order of 50 meters per second, which confirms the slow speed observed experimentally (see p. 280). Furthermore, the basilar membrane undergoes maximal displacement at a position which is a function of frequency. The maximum is near the helicotrema at low and near the oval window at high frequencies. In addition to the maximal displacement, there is a maximal pressure gradient across, or through, the membrane which also occurs at different places for different frequencies. The pressure gradient does not occur in the same phase and position as the displacement.

It is conceivable, as Reboul points out, that the stimulating factor for the end-organ (hair-cells) is the distortion produced by this pressure gradient itself, rather than the distortion produced by a displacement of the membrane. Experimental evidence has not as yet decided this point (see, however, p. 343).

This point of view regarding the dynamics of the cochlea

which considers the acoustic stimulus as a propagated disturbance in an elastic tube, rather than as a forced vibration impressed upon a set of resonators, has the additional advantage that it enables us to see how the cochlea can behave as an analyzer in spite of a large damping factor. A simple system which is critically damped will not have a maximum in its resonance-curve (cf Fig 3, p 12, and see A H Davis, p 15) and a set of such systems could not, therefore, serve as an analyzer. Hence, if we were to treat the cochlea as a set of resonant systems, we should have to assume a damping less than critical. No such restriction is necessary, however, when we treat the cochlea as a hydrodynamic system in an elastic tube, for a maximum of displacement of the basilar membrane can be obtained in spite of a large damping factor. Thus it is possible for the basilar membrane to act as an analyzer, and at the same time show no free vibrations after a stimulus has ceased.

The following table relates ratios to decibels. When we know the ratio of two pressures or velocities in a plane progressive sound wave, or of two currents or voltages operating in the same or equal impedances, we can find the corresponding number of decibels by entering the table.

Power ratios can be converted into decibels by means of the simple rule that the number of decibels corresponding to a given ratio of powers is one-

Voltage Ratio	00	01	02	03	04	05	06	07	08	09
10	000	006	172	257	341	424	506	588	668	749
11	826	866	684	1062	1433	1814	2200	2584	2968	3351
12	1584	1656	1727	1798	1868	1938	2007	2076	2144	2212
13	2279	2345	2411	2477	2542	2607	2671	2734	2796	2860
14	2923	2984	3046	3107	3167	3227	3287	3346	3405	3464
15	3522	3580	3637	3694	3750	3807	3862	3918	3973	4028
16	4082	4137	4190	4244	4297	4350	4402	4454	4506	4558
17	4606	4659	4711	4761	4811	4861	4910	4958	5006	5057
18	5103	5154	5201	5246	5295	5343	5390	5437	5483	5529
19	5575	5621	5668	5711	5758	5801	5845	5888	5933	5977
20	6021	6064	6107	6150	6193	6235	6277	6319	6361	6403
21	6444	6486	6527	6568	6608	6648	6688	6728	6768	6808
22	6848	6888	6927	6968	7008	7047	7087	7127	7167	7207
23	7245	7285	7324	7364	7403	7442	7481	7520	7559	7598
24	7637	7676	7715	7754	7793	7832	7871	7910	7949	7988
25	8027	8065	8104	8142	8181	8219	8257	8296	8334	8373
26	8411	8449	8487	8525	8563	8601	8639	8677	8715	8753
27	8791	8828	8866	8904	8941	8979	9016	9054	9091	9129
28	9166	9203	9240	9277	9314	9351	9388	9425	9462	9499
29	9536	9572	9609	9645	9682	9718	9755	9791	9828	9864
30	9901	9937	9973	10000	10036	10072	10108	10143	10179	10214
31	10250	10285	10320	10355	10390	10425	10460	10495	10530	10565
32	10600	10635	10670	10705	10740	10775	10810	10845	10880	10915
33	10950	10985	11020	11055	11090	11125	11160	11195	11230	11265
34	11300	11335	11370	11405	11440	11475	11510	11545	11580	11615
35	11650	11685	11720	11755	11790	11825	11860	11895	11930	11965
36	12000	12035	12070	12105	12140	12175	12210	12245	12280	12315
37	12350	12385	12420	12455	12490	12525	12560	12595	12630	12665
38	12700	12735	12770	12805	12840	12875	12910	12945	12980	13015
39	13050	13085	13120	13155	13190	13225	13260	13295	13330	13365
40	13400	13435	13470	13505	13540	13575	13610	13645	13680	13715
41	13750	13785	13820	13855	13890	13925	13960	13995	14030	14065
42	14100	14135	14170	14205	14240	14275	14310	14345	14380	14415
43	14450	14485	14520	14555	14590	14625	14660	14695	14730	14765
44	14800	14835	14870	14905	14940	14975	15010	15045	15080	15115
45	15150	15185	15220	15255	15290	15325	15360	15395	15430	15465
46	15500	15535	15570	15605	15640	15675	15710	15745	15780	15815
47	15850	15885	15920	15955	15990	16025	16060	16095	16130	16165
48	16200	16235	16270	16305	16340	16375	16410	16445	16480	16515
49	16550	16585	16620	16655	16690	16725	16760	16795	16830	16865
50	16900	16935	16970	17005	17040	17075	17110	17145	17180	17215
51	17250	17285	17320	17355	17390	17425	17460	17495	17530	17565
52	17600	17635	17670	17705	17740	17775	17810	17845	17880	17915
53	17950	17985	18020	18055	18090	18125	18160	18195	18230	18265
54	18300	18335	18370	18405	18440	18475	18510	18545	18580	18615
55	18650	18685	18720	18755	18790	18825	18860	18895	18930	18965
56	19000	19035	19070	19105	19140	19175	19210	19245	19280	19315
57	19350	19385	19420	19455	19490	19525	19560	19595	19630	19665
58	19700	19735	19770	19805	19840	19875	19910	19945	19980	20015
59	20050	20085	20120	20155	20190	20225	20260	20295	20330	20365

half of the number corresponding to the same ratio of voltages. In other words, when dealing with power, find from the table the number of decibels corresponding to the desired ratio and divide by 2.

For ratios outside the range of this table add 20 db for every tenfold increase. (Courtesy General Radio Co)

Voltage Ratio	00	01	02	03	04	05	06	07	08	09
60	15 563	15 572	15 592	15 906	15 621	15 635	15 649	15 664	15 678	15 692
61	15 707	15 721	15 735	15 749	15 763	15 776	15 792	15 806	15 820	15 834
62	15 848	15 862	15 876	15 890	15 904	15 918	15 931	15 945	15 959	15 973
63	15 987	16 001	16 014	16 035	19 042	19 055	19 069	16 083	16 096	16 110
64	16 124	16 137	16 151	16 164	19 178	16 191	16 205	16 218	16 232	16 245
65	16 259	16 272	16 285	16 296	16 312	16 325	16 338	16 351	16 365	16 378
66	16 391	16 404	16 417	16 430	16 443	16 456	16 469	16 483	16 496	16 509
67	16 521	16 534	16 547	16 560	16 573	16 586	16 599	16 612	16 625	16 637
68	16 650	16 663	16 676	16 688	19 701	19 714	16 726	16 739	16 752	16 764
69	16 777	16 790	16 802	16 815	16 827	19 840	16 852	16 865	16 877	16 890
70	16 902	16 914	16 927	16 939	16 951	16 964	16 976	16 988	17 001	17 013
71	17 025	17 037	17 050	17 062	17 074	17 086	17 098	17 111	17 122	17 135
72	17 147	17 159	17 171	17 183	17 195	17 207	17 219	17 231	17 242	17 255
73	17 266	17 279	17 290	17 302	17 314	17 326	17 338	17 349	17 361	17 373
74	17 385	17 398	17 408	17 420	17 431	17 443	17 455	17 466	17 478	17 490
75	17 501	17 513	17 524	17 536	17 547	17 559	17 570	17 582	17 593	17 605
76	17 616	17 628	17 639	17 650	17 662	17 673	17 685	17 696	17 707	17 719
77	17 730	17 741	17 752	17 764	17 775	17 786	17 797	17 808	17 820	17 831
78	17 841	17 853	17 864	17 875	17 886	17 897	17 908	17 919	17 931	17 942
79	17 953	17 964	17 975	17 985	17 998	18 007	18 018	18 029	18 040	18 051
80	18 062	18 073	18 083	18 094	18 105	18 116	18 127	18 137	18 148	18 159
81	18 170	18 180	18 191	18 202	18 212	18 223	18 234	18 244	18 255	18 266
82	18 276	18 287	18 297	18 308	18 319	18 329	18 340	18 350	18 361	18 371
83	18 382	18 392	18 402	18 413	18 423	18 434	18 444	18 455	18 465	18 475
84	18 486	18 496	18 506	18 517	18 527	18 537	18 547	18 558	18 568	18 578
85	18 588	18 599	18 609	18 619	18 629	18 639	18 649	18 659	18 670	18 680
86	18 690	18 700	18 710	18 720	18 730	18 740	18 750	18 760	18 770	18 780
87	18 790	18 800	18 810	18 820	18 830	18 840	18 850	18 860	18 870	18 880
88	18 890	18 900	18 909	18 919	18 929	18 939	18 949	18 958	18 968	18 976
89	18 986	18 998	19 007	19 017	19 027	19 039	19 046	19 056	19 066	19 075
90	19 085	19 094	19 104	19 114	19 123	19 133	19 143	19 152	19 162	19 171
91	19 181	19 190	19 200	19 209	19 218	19 226	19 238	19 247	19 257	19 266
92	19 276	19 285	19 295	19 304	19 313	19 323	19 332	19 342	19 351	19 360
93	19 370	19 379	19 386	19 398	19 407	18 419	19 426	19 435	19 444	19 453
94	19 463	16 472	19 481	16 490	19 499	16 509	16 516	16 527	19 536	19 545
95	19 554	19 564	19 573	19 582	19 591	19 600	19 609	19 616	19 627	19 636
96	19 645	19 654	19 664	19 673	19 682	16 691	19 700	19 709	19 718	19 726
97	19 735	19 744	19 753	19 762	19 771	16 780	19 789	19 796	19 807	19 816
98	19 825	19 833	19 842	19 851	19 860	19 869	19 878	19 886	19 895	19 904
99	19 913	19 921	19 930	19 939	19 943	19 959	19 965	19 974	19 983	19 993

[illegible]

GLOSSARY

Absolute pitch Absolute pitch refers to the ability possessed by certain people to name the musical pitch of a note without the aid of a standard of reference

Acoustic impedance The acoustic impedance of a sound medium on a given surface lying in a wave front is the complex quotient of the sound pressure (force per unit area) on that surface by the flux (volume velocity, or linear velocity multiplied by the area) through the surface When concentrated rather than distributed impedances are considered, the impedance of a portion of the medium is defined by the complex quotient of the pressure-difference, effective in driving that portion, by the flux (volume velocity) The acoustic impedance may be expressed in terms of mechanical impedance, the acoustic impedance is equal to the mechanical impedance divided by the square of the area of the surface considered The unit is the acoustic ohm

Acoustic ohm. An acoustic resistance, reactance, or impedance is said to have a magnitude of one acoustic ohm when a sound pressure of 1 dyne per square centimeter produces a volume velocity of 1 cc per sec

Action potential An action potential is the electric potential generated between an active and an inactive region in a living tissue whenever an element of the tissue (nerve or muscle fiber) is activated The energy generating the action potential is supplied by the metabolic processes of the tissue and not by the stimulus to activation The action potential behaves in an all-or-none fashion (Cf distortion potential)

The distinction between action potential and action-current is as follows

Action-current is the current, derived from a living tissue, which flows in an external circuit as a result of the electrochemical processes associated with functional activity of the elements of the tissue

Action potential is the difference of electric potential generated between two points in a tissue as a result of its functional activity The action potential is measured by an instrument which draws a negligible amount of current

Attribute A tonal attribute is an aspect of the sensation produced by a tonal stimulus Each attribute is defined by a differential reaction to a tone by a listener under a particular set, or *Aufgabe* Four aspects

can be distinguished in stimulation by pure tones. They are pitch, loudness, volume, and density.

Audiogram An audiogram is a graph expressing hearing loss as a function of frequency.

Azimuth The azimuth of a sound refers to the angular direction of the source relative to the listener.

Beats Beats are the periodic variations of the amplitude of the sound pressure at a point due to the interference of two sound waves of different frequencies.

Bel (b) The bel is the unit of a logarithmic scale expressing the ratio of two amounts of power. The number of bels denoting such a ratio is the logarithm to the base 10 of this ratio.

Combination tone A combination tone is produced when two tones act simultaneously on a nonlinear transducer. The combination tone may have a frequency equal to the difference between the two tones or any of their harmonics (difference tones), or it may have a frequency equal to the sum of two tones or any of their harmonics (summation tones).

Cycle (\sim) One complete set of the recurrent values of a periodic quantity comprises a cycle. (Cf frequency.)

Decibel The decibel is one tenth of a bel. The number of decibels denoting the ratio of two amounts of power is 10 times the logarithm to the base 10 of this ratio. The abbreviation db is commonly used for the term decibel.

When the conditions are such that ratios of currents or ratios of voltages (or analogous quantities in other fields such as pressures, amplitudes, or particle velocities in sound) are the square roots of the corresponding power ratios, the number of decibels by which the corresponding powers differ is expressed by the following formulas:

$$n = 20 \log_{10} (I_1/I_2) \text{db}$$

$$n = 20 \log_{10} (V_1/V_2) \text{db}$$

where I_1/I_2 and V_1/V_2 are the given current and voltage ratios respectively.

By extension, these relations between numbers of decibels and ratios of currents or voltages are sometimes applied where these ratios are not the square roots of the corresponding power ratios but, to avoid confusion, such usage should be accompanied by a specific statement of this application. (See Appendix III for a table relating voltage ratios to decibels.)

Density. Density is that aspect of auditory sensation in terms of which sounds may be ordered on a scale running from 'dense' to 'diffuse'. The density of a tone increases with increased intensity and also with increased frequency.

Dichotic stimulation. Dichotic stimulation refers to the simultaneous stimulation of both ears, but with a different stimulus in each ear.

Difference-limen (DL). The difference limen is defined as the minimal increment in a stimulus needed to produce a just noticeable difference in sensation. The relative difference limen is the ratio of the DL to the value of the stimulus to which it is added.

Distortion potential. A distortion potential is the electric potential generated by the deformation of a living cell. The energy of the distortion potential is supplied by the distorting force, and the distortion potential does not behave in all-or none fashion. (Cf. action potential.)

Dyne per square centimeter. A dyne per square centimeter is the unit of sound pressure. A dyne is defined as the force which will produce a change of velocity of one centimeter per second in a gram mass in one second.

Electrophonic effect. The electrophonic effect refers to the ability of an alternating current, of suitable frequency and intensity, to arouse a sensation of hearing when passed through a person's head.

Equilibration. Equilibration refers to the process by which the activity in a nerve subjected to repetitive stimulation achieves a steady state. The initial burst of activity in a nerve, as measured by the action potential, is greater than the final level of activity reached after prolonged stimulation.

Forced vibration. A forced vibration is any vibration which is imposed upon a system by an external force and whose frequency is controlled thereby.

Fourier's theorem. Any function which, within an interval, is single valued, finite, and continuous may be represented by a series of sinusoidal functions whose frequencies are in harmonic relation. The application of this theorem is not limited to periodic functions.

Free wave (free progressive wave). A free wave is a sound wave free from interference-effects.

Frequency. The number of cycles occurring per unit of time, or which would occur per unit of time if all subsequent cycles were identical with the cycle under consideration, is the frequency. The frequency is the reciprocal of the period. The unit is the cycle per second. The

expression *cycles per second* is usually reduced to the single word *cycles* wherever this usage is unambiguous

Fundamental frequency. A fundamental frequency is the lowest component frequency of a periodic wave or quantity

Harmonic A harmonic is a component of a periodic wave or quantity having a frequency which is an integral multiple of the fundamental frequency For example, a component whose frequency is twice the fundamental frequency is called the second harmonic

An **aural harmonic** is a harmonic generated in the ear as a result of nonlinearity and asymmetry in the auditory transducer

Hearing loss Hearing loss is measured as the number of decibels that the intensity of a tone must be raised beyond the normal threshold value for that tone, in order that a deafened ear may detect it The percentage of hearing loss at a given frequency is 100 times the ratio of the hearing loss in decibels to the number of decibels between the normal thresholds of audibility and of feeling at that frequency

Intensity Intensity refers to a dimension of a stimulus It is a measure of the strength or magnitude of the stimulating agent In plane progressive sound waves, intensity is usually measured in terms of pressure or energy flow (power), but, whenever the power is not proportional to the square of the pressure, energy flow alone should be taken as the measure of intensity (See *sound intensity*)

Intensity level The intensity level, in decibels, of a sound is 10 times the logarithm to the base 10 of the ratio of the intensity I of this sound, to the reference intensity I_0 In other words, intensity level is the number of decibels that a sound is above the reference intensity

Interference pattern An interference pattern is the spatial distribution of pressure, particle velocity, energy density, or energy flux which occurs when sound waves of the same frequency are superposed

Isophonic contours An isophonic contour gives the values of frequency and intensity, of a pure tone, which produce a sensation, one of whose attributes has a constant value Isophonic contours are plots of frequency vs intensity with the tonal attributes as parameters The isophonic contours comprise contours of equal pitch, equal loudness, equal volume, and equal density

Loudness Loudness is that aspect of auditory sensation in terms of which sounds may be ordered on a scale running from 'soft' to 'loud' Loudness is chiefly a function of the intensity of a sound, but it is also dependent upon the frequency and the composition The unit is the sone

Loudness level. The loudness level of a sound is the intensity level of a 1000-cycle tone which sounds equal to the sound in loudness. Loudness-level is measured in decibels or phons above the reference intensity. The 1000-cycle tone is the reference tone for loudness-comparisons, and the loudness level of all other sounds is expressed in terms of the equally loud reference tone.

Masking. Masking is defined as the number of decibels by which a listener's threshold of audibility for a given tone is raised by the presence of another sound. The graph showing the elevation of the threshold for various frequencies due to a masking sound is known as the masking audiogram of that sound.

Mechanical impedance. The mechanical impedance of a system is the complex quotient of the alternating force applied to the system by the resulting alternating linear velocity in the direction of the force at its point of application. The unit is the mechanical ohm or the dyne second per centimeter.

Mel. The mel is a unit of pitch. It is so defined that a 1000-cycle tone 40 db above threshold has a pitch of 1000 mels. (The mel is a so-called 'subjective' unit.)

Microphonic. A microphonic is the electric potential produced by a transducer which converts vibratory into electrical energy. The alternating potential produced by the cochlea in response to a stimulating sound is an aural or cochlear microphonic.

Modulation. Any periodic alteration of a parameter of a vibratory phenomenon produces modulation. Modulations of sound waves can be produced by varying the frequency, the intensity, or the phase of the wave.

Natural frequency. The natural frequency of any system is the frequency at which its vibrating element will vibrate after the external force displacing it from its normal position has ceased to act. The unit is the cycle per second.

Natural period. The natural period is the reciprocal of the natural frequency. The unit is the second.

Neuron. A neuron is an entire nerve-cell, including cell body, axon and dendrites.

Octave. An octave is the interval between two frequencies having a ratio of 2 to 1. One octave is equal to 1200 musical cents.

Operating point. The operating point of an electrical or mechanical system which is subject to alternating forces is its position or state when no alternating force is applied. Under an alternating force the system moves back and forth about its operating point.

- Overtone** An overtone is a partial having a frequency higher than that of the basic frequency
- Partial** A partial is a component of a complex tone. Its frequency may be either higher or lower than that of the basic frequency and may or may not bear an integral relation to the basic frequency
- Particle-velocity** The particle velocity in a sound wave is the instantaneous velocity of a given infinitesimal part of the medium, with reference to the medium as a whole, due to the passage of the sound wave
- Period (T)** The time required for one cycle of a periodic quantity is the period. The unit is the second
- Phase** The phase of a sound wave, at a given instant, is the part of the cycle in which the wave finds itself at that instant, relative to some arbitrary reference point. Phase is measured in degrees or radians
- Phon** The phon is a unit for measuring the loudness level of a tone. The number of phons is equal to the number of decibels that a 1000 cycle tone is above the reference intensity when judged equal in loudness to the tone in question
- Piezoelectricity** Piezoelectricity is the electricity or electric polarity produced by pressure on an appropriate body. Certain crystallized substances such as quartz, commonly exhibit a piezo (pressure) effect
- Pitch** Pitch is that aspect of auditory sensation in terms of which sounds may be ordered on a scale running from low to 'high'. Pitch is chiefly a function of the frequency of a sound but it is also dependent upon the intensity and the composition. The unit is the mel
- Pressure level** The pressure level in decibels of a sound is twenty times the logarithm to the base 10 of the ratio of the pressure P of this sound to the reference pressure P_0 . Unless otherwise specified, the reference pressure is understood to be 0.0002 dyne per square centimeter
- Pure tone** A pure tone is a sound produced by an instantaneous sound pressure which is a simple sinusoidal function of time
- Reference-frequency** The reference frequency or reference tone, for loudness-comparisons is a tone of 1000 cycles per second
- Reference intensity (I_0)** The reference intensity in acoustics is taken as 10^{-12} watt per square centimeter. In a plane progressive sound wave in air, this value corresponds to a root mean square pressure of 0.0002 dyne per square centimeter
- Refractory period** The refractory period is the period of time following the excitation of a nerve or muscle fiber, during which the fiber is either absolutely or relatively inexcitable

Resonance (velocity resonance) Resonance exists between a body, or system, and an applied sinusoidal force if any small change in the frequency of the applied force causes a decrease in velocity at the driving point, or if the frequency of the applied force is such that the absolute value of the driving point impedance is a minimum

Resonant frequency A resonant frequency is a frequency at which resonance exists The unit is the cycle per second

Sensation level The sensation level of a given sound is the number of decibels that the sound is above its normal threshold of audibility

Sone The sone is a unit of loudness It is defined as the loudness of a 1000-cycle tone 40 db above threshold (The sone is a so-called 'subjective' unit) A millisone is one thousandth of a sone

Sound. (a) Sound is an alteration in pressure, particle-displacement, or particle velocity propagated in an elastic material, or the superposition of such propagated alterations

(b) Sound is also the sensation produced through the ear by the alterations described above

Sound-energy density (E) Sound-energy density is the sound-energy per unit volume The unit is the erg per cubic centimeter

Sound-energy flux (J) The sound-energy flux is the average over one period of the rate of flow of sound-energy through any specified area The unit is the erg per second

Sound intensity (I) The sound intensity of a sound field in a specified direction at a point is the sound-energy transmitted per unit of time in the specified direction through a unit area normal to this direction at the point The unit is the erg per second per square centimeter, but sound intensity may also be expressed in watts per square centimeter

Sound pressure The effective sound pressure at a point is the root mean square value of the instantaneous sound pressure over a complete cycle, at that point The unit is the dyne per square centimeter

Spectrum A spectrum is the distribution of energy among the component frequencies of a vibratory phenomenon An acoustic spectrum refers to the frequencies, intensities, and phases of the components of a sound

Subharmonic A subharmonic is a component of a complex wave having a frequency which is an integral submultiple of the basic frequency

Synapse A synapse is the connection or region of contact between two neurons A nerve impulse progressing along the axon of one nerve-cell must cross a synapse before reaching the dendrite or cell body

of the next nerve-cell The transmission of impulses across synapses is subject to different laws from those governing transmission in nerve fibers

Synchronized action potentials Action potentials in different nerve fibers are said to be synchronized with one another when they arrive at a given point in the nerve within an interval of time which is short relative to the duration of the action potentials They are synchronized with sound waves when they are initiated in a definite phase relation with the sound waves

Thermal noise A thermal noise is the noise produced by the random vibration of the molecules of the air due to thermal agitation Thermal noise is also produced when the potential due to the random agitation of electrons in an electrical conductor is amplified and impressed on a loud speaker In a thermal noise all frequencies are present and the spectrum of the sound is continuous

Threshold of audibility The threshold of audibility at any specified frequency is the minimal value of sound pressure which produces a tonal sensation In specifying the threshold value of sound pressure, the point at which the pressure is measured must be stated

Transducer A transducer is a device by means of which energy may flow from one or more transmission systems to one or more other transmission systems A microphone is a transducer, because by means of it, energy flows from an acoustic into an electrical system Likewise the ear is a transducer

Utilization time Utilization time is the minimal duration in which a stimulus of given intensity is effective in initiating a nerve impulse

Vibrato The vibrato is a musical embellishment consisting of a rapid rise and fall in the frequency (or intensity) of a note at the rate of about seven fluctuations per second

Volume Volume is that aspect of auditory sensation in terms of which sounds may be ordered on a scale running from 'small' to 'large' The volume of a tone increases with increased intensity but decreases with increased frequency

The word 'volume' is commonly used by radio engineers to refer to the intensity of a sound and should not be confused with *volume* as defined above

Wave-length (λ) The wave length of a periodic wave in an isotropic medium is the perpendicular distance between two wave fronts in which the displacements have a phase-difference of one complete cycle

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